3D printing technologies in the food system for food production and packaging

Area of research interest: Emerging challenges and opportunities
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3D printing: 3D printing or additive manufacturing is the construction of a three-dimensional object from a CAD or digital 3D model file. It can be done with a variety of materials and printing processes in which material is deposited, joined or solidified under computer control, with material being fused together, typically layer by layer.

Additive manufacturing/ Additive layer manufacturing: Additive manufacturing (AM) or additive layer manufacturing (ALM) is the industrial production name for 3D printing, a computer controlled process that creates three dimensional objects by depositing materials, usually in layers.

Binder jetting: A binder liquid is dispensed via the printer nozzle in the x- and y-axes onto a food powder bed. After each layer is solidified, usually by applying heat to speed up drying, a new layer of powder is applied to the powder bed via a re-coater and the process is repeated after lowering the powder bed table in the z- direction.

Directed energy deposition: Directed Energy Deposition (DED) allows for the creation of objects by melting the material (most frequently used for metals such as titanium, aluminium, stainless steel or copper) in powder form, or as a wire/filament with a focused energy source that melts the metal as it is deposited by a nozzle on a surface.

Extrusion based printing: Extrusion of viscous and semi-viscous materials including food ingredients, often called food inks, through a nozzle via a pump mechanism. A number of extrusion mechanisms exist but the most common are, syringe-based, air pressure based, or screw-based.

Food ink: Viscous or semi-viscous paste of food ingredients used for 3D printing of food.

Fused deposition modelling: Fused deposition modelling (FDM), also called fused filament fabrication (FFF) is a 3D printing method, which uses a continuous filament that is extruded through a heated printer head/nozzle.

Fused filament fabrication: Builds a 3D object by heating up a material filament before extrusion that solidifies while binding onto the previous layer.

Hot air sintering: Hot air sintering, similar to SLS but sintering facilitated by a beam of hot air rather than a laser.

Hot melt extrusion: Nozzle of extrusion-based printer is heated to facilitate extrusion.

Ink jet printing: Is not strictly a 3D method for creating layered structures but rather for dispensing mostly low viscosity/liquid food ink droplets onto the surface of food items in a patterned fashion mainly for decorative purposes or surface filling. The nozzle of inkjet printers does not touch the food onto which is printed.

Material extrusion: Material, liquid or paste, extruded through a nozzle.

Material jetting: Material jetting creates objects in a similar method to a two-dimensional ink jet printer. Material is jetted onto the build surface or platform, where it solidifies in order to build up an object layer by layer.

Powder bed fusion: Powder bed fusion (PBF) methods use either a laser or electron beam to melt and fuse material powder together in order to create 3 dimensional objects. This includes the methods of selective laser sintering (SLS) and multi-jet fusion (MJF) technologies.

Selective laser sintering: Selective laser sintering (SLS) is an additive manufacturing (AM) technique that uses a laser as the power and heat source to sinter powdered material (most commonly polymers), aiming at points in space defined by a 3D digital model to create the object.

Sheet lamination: Sheet lamination is an additive manufacturing (AM) methodology where thin sheets of material (usually supplied via a system of feed rollers) are bonded together layer-by-layer to form a single piece that is cut into a 3D object.

Surimi: Surimi is a paste made from fish or other meat, often from waste streams. The term can also refer to a number of East Asian foods that use that paste as their primary ingredient.

Vat photopolymerisation: Vat polymerisation uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer using a focused ultraviolet (UV) light beam that cures or hardens the resin where required.

Executive summary: 3D printing technologies in the food system for food production and packaging

3D printing, also called additive manufacturing, represents a range of technologies that create 3D objects through a layer-by-layer deposition process using digital image files. 3D printing evolved over the past four decades from a prototyping tool to a manufacturing method in its own right in a number of industries and several additive manufacturing processes have matured into robust production technologies for highly customised and bespoke products when produced in small numbers. However, 3D printing technologies at their current stage of evolution are usually not considered commercially viable for mass production applications.

3D printing of food

3D printing of food emerged around 15 years ago promoted by 3D technology enthusiasts and academic engineering departments experimenting with foodstuffs, mostly chocolate or sugar-based, that could be printed at the time with generic 3D printers. Over the past decade a number of startups, have developed 3D printers optimised for some food ingredients, and at present a small number (globally fewer than 10) of different 3D food printers are commercially available for consumers. In addition, a limited B2B market for printers is emerging for use mainly in the confectionery and fine dining sector for the production of foodstuffs with personalised or customised shapes. At present a small number of startups (globally less than 20) are offering 3D food printing services, either through the sales of customised 3D printed food items or by offering these as part of a dining experience either in a restaurant or at events. In addition, a handful of large international food processing companies or kitchen appliance manufacturers have shown some limited engagement with the technology for around a decade, either through in-house R&D or patenting activity, or by entering collaborations with academic research departments or food printer manufacturing startups.

Over the past five years, academic research into the technical possibilities and challenges of food 3D and 4D printing, as well as media reporting on the technology has rapidly increased. In addition, several emerging niche applications for 3D food printing (3DFP) are currently tested and promoted by a few commercial players, such as 3D printed personalised nutrition or texturising of foods for patients with difficulties eating regular food in hospitals and care homes. Adaptations of the technology to such specific sub-niches indicate that 3D printing might act as an enabling or supporting technology for other technology-enabled trends in the food system, such as personalised nutrition, use of alternative proteins or food side- or waste streams, plant-based meat and cultured meat analogues, functional foods and health nutrition. Moreover, food printing currently appears to evolve from a focus on the shape aspect of printed foods towards exploring solutions for food processing challenges and novel ways to modify textures and the sensory experience of certain foodstuffs in an area that could be described as food product prototyping. Very recent innovations, such as 4D printing applications for food in which the texture, colour, taste, or shape of the printed item change over time, or upon external stimuli, are at an early stage and need to become still more robust and cost effective before they might add value to products and enter wider consumer markets.

Despite increasing research and exploration of such potential application areas, 3D and 4D printing of food is at present still a curiosity niche phenomenon, most advanced possibly in the fine dining and confectionery segment for the production of edible and personalised decorative food items, mostly chocolate- or sugar-based. However, current maturity levels of the few commercially available food printers, some service offerings on the market, and continuous low-level engagement of large food producers with the technology, are indicative of the potential of 3D food printing to be able to reach wider consumer markets via different channels in the next five to ten years.

Selected key findings

- Despite increasing R&D activity and the development of specific food printers optimised for a limited number of foodstuffs, such as chocolate, sugar, dough-based, fruit gels, or cheese, commercial viability of the technology still needs to be proven. Globally a very low number of commercially active 3DFP operators exist currently (< 20).
- Peak academic research and patenting was observed over the past five years with a total number of publications directly related to 3DFP of around 150 and a small number of relevant patents over the past decade with few patent holders holding more than one patent.
- Most of the academic literature is concerned with the technical aspects of formulating printable food inks and with optimising printing conditions using various additives such as hydrocolloids, indicating that additives are essential for 3DFP to enable the technical printing process.
- Existing food printers are using mainly extrusion-based printing technology and physical and chemical characterisation of viscosity and rheology of food inks is a major technical research concern as most food ingredient mixtures are still difficult to print.
- Trends in R&D indicate that healthy and functional foodstuffs, such as fruit- and vegetable-based as well as various proteins, including novel sources of proteins such as from plants, insects or algae, are currently explored for their suitability to be 3D printed at scale.
- Modified 3D printing technology is currently applied in the plant-based and cultured meat alternatives sectors to improve texture of products.
- Consumer knowledge of and interest in 3DFP is very limited at present.
- Despite discussion in the academic literature of potential wider impacts of the technology on the food system, for example through more localised supply chains, or claims to be able to contribute to sustainability, it is recognised that these claims are at the present stage of technology readiness and commercial maturation highly speculative and at least 5-10 years away from realisation.
- Future evolution of the 3DFP field is expected to be slow due to technical challenges, such as slow printing speeds and technical issues around print quality and the requirement of expert pre-processing of ingredients and optimisation of printer settings. Hence, the B2B printer and services market may evolve quicker than the B2C market.
- At present 3DFP is not directly regulated anywhere in the world and food safety issues around the technology are not well understood beyond common sense arguments, such as that printer parts need to be easy to clean and cleaned regularly etc.
- Potential regulatory aspects of 3DFP technology are discussed in the academic literature and highlight a possible labelling requirement of 3D printed food as novel foods, or as highly processed foods depending on food type printed.

3D printing of food packaging

Use of 3D printing technologies for the production of (primary) food packaging is at present very limited and available information on the subject indicates a role mainly in prototyping of food packaging, such as for containers, bottles, boxes, etc, while final food packaging is still produced via cheaper existing mass production technologies. Small startups occasionally use 3D printing to demonstrate functionality of novel packaging materials or concepts, and large packaging manufacturers occasionally 3D-print moulds for the mass production processes of some packaging to save engineering costs. In the academic literature 3D printing of novel, for example sustainable, packaging materials is explored and the possibility to use 3D printing to manufacture elements for smart packaging sensors has been discussed. However, at present 3D printing technology is not robust enough and commercially not competitive compared to other existing mass production technologies for food packaging.

Selected recommendations for the FSA

Short-term FSA priorities (within 3 years)

- Identify hubs and nodes of the emerging 3DFP ecosystem.
- Set standards for labelling early in the technology evolution, as different printing technologies subject foodstuffs to different physical and chemical parameters as well as additives. This may impact the nature and nutritional properties of the end product.
- Develop safety and hygiene standards for the emerging categories of printing processes.
- Engage with academia and research institutions that work on 3DFP technology to understand impacts of pre- and post-processing of printed foodstuffs and respective printing processes on FSA remit areas.

Medium term FSA priorities (3-5 years)

- Continue research on the impact of pre-processing, printing and post-processing on natural and nutritional properties of 3D printed food.
- Consider assessment frameworks for the validity of claims made by 3DFP actors, such as on nutritional quality, health, sustainability, and if necessary devise relevant regulation.

Long-term FSA priorities (5-10+ years)

- Continue research on health impact of long-term consumption of 3D printed foods.
- Establish standards of what printable foodstuff formulations (inks/pastes) are permitted with their longer-term impacts on health/consumers in mind.

Introduction: 3D printing technologies in the food system for food production and packaging

This introduction is a top-level overview of the field of 3D food printing (3DFP) focusing on its historical evolution and current trends that may impact on the food system, providing the wider context within which 3D printing is analysed in this report, with areas of importance for the FSA remit highlighted. Due to the limited amount of information available on the current use of 3D printing technologies for the production of food packaging, this topic is presented separately in chapter 4 of this report.

1.1 The context of 3D printing

3D printing, also called additive manufacturing, represents a range of technologies that creates 3D objects through a layer-by-layer deposition process using digital image files, usually generated in Computer Aided Design (CAD) software. As 3D printing has evolved over the past four decades, a number of technical additive manufacturing concepts have matured into robust individual technologies, as defined by the American Society for Testing and Materials (ASTM) International Committee F42 on Additive Manufacturing Technologies. These are at present: vat photopolymerisation, powder bed fusion, material extrusion, material jetting, binder jetting, directed energy deposition and sheet lamination (ASTM International, 2022). Commercially available printers deploying these engineering concepts for specific applications and materials have found their places in various industries, each with their own strengths and weaknesses and at very different price points. Despite this variety of technical printing approaches the currently most widely used 3D printers, also in consumer markets, deploy a form of Fused Deposition Modelling (FDM), sometimes also referred to as Fused Filament Fabrication (FFF), based on extrusion of a thermoplastic material that hardens after being deposited through a heated filament nozzle. With regards to the material deposition process, FDM/FFF is an extrusion-based printing method, as opposed to other methods that build structures for example via photopolymerisation of liquid substrates, or fusion of powder particles. Generally, 3D printing is considered today a valid technology where highly customised and bespoke products need to be made in small numbers, often in a decentralised fashion, such as in the case of spare parts in remote locations, as it saves the costs and time of engineering a specific manufacturing process to make the product as well as supply logistics. Moreover in design, art and fashion 3D printers have found their place for creating unique complex designs (Gebhardt et al., 2018; Shahrubudin et al., 2019).

After a slow evolution over the past four decades 3D printing has now reached a level of maturity that it enables viable commercial applications at scale in a number of industries. While early applications of 3D printing were focusing on complex shapes and rapid prototyping, the technology can today deliver in some areas a reproducibility and quality of final products such that it is now considered an industrial manufacturing process in its own right. From buildings to tissues assembled from human cells, a wide range of input materials such as polymers, including bio-polymers and various resins, metals and ceramics among others can be used today for the production of complex structures using 3D printing technologies (Derossi et al., 2021; Patra & Young, 2016; Tay et al., 2017).

Associated with these capabilities, new business models have been developed making 3D printers and 3D printing services and products available to wider consumer and B2B markets. However, while for some lower-throughput applications 3D printing can today replace other production methods, it is also acknowledged that it is on the whole still a slow performing technology with well understood limitations, and where alternative methods in particular for mass production exist, 3D printing would in most cases still not be cost effective, or able to deliver the consistency and quality of final product required (Gebhardt et al., 2018).

1.2 3D printing of food – past evolution

The concept of producing food via some digitally operated machine is often traced back to science fiction novels and the “replicator machine” featured in the 1960s original Star Trek series. The earliest attempts to seriously propose engineering solutions for 3DFP go back to around 2001 when Nanotech Instruments Inc. filed a patent for a 3D fabrication method to produce customised birthday cakes, however without at the time building a physical prototype of the suggested device.

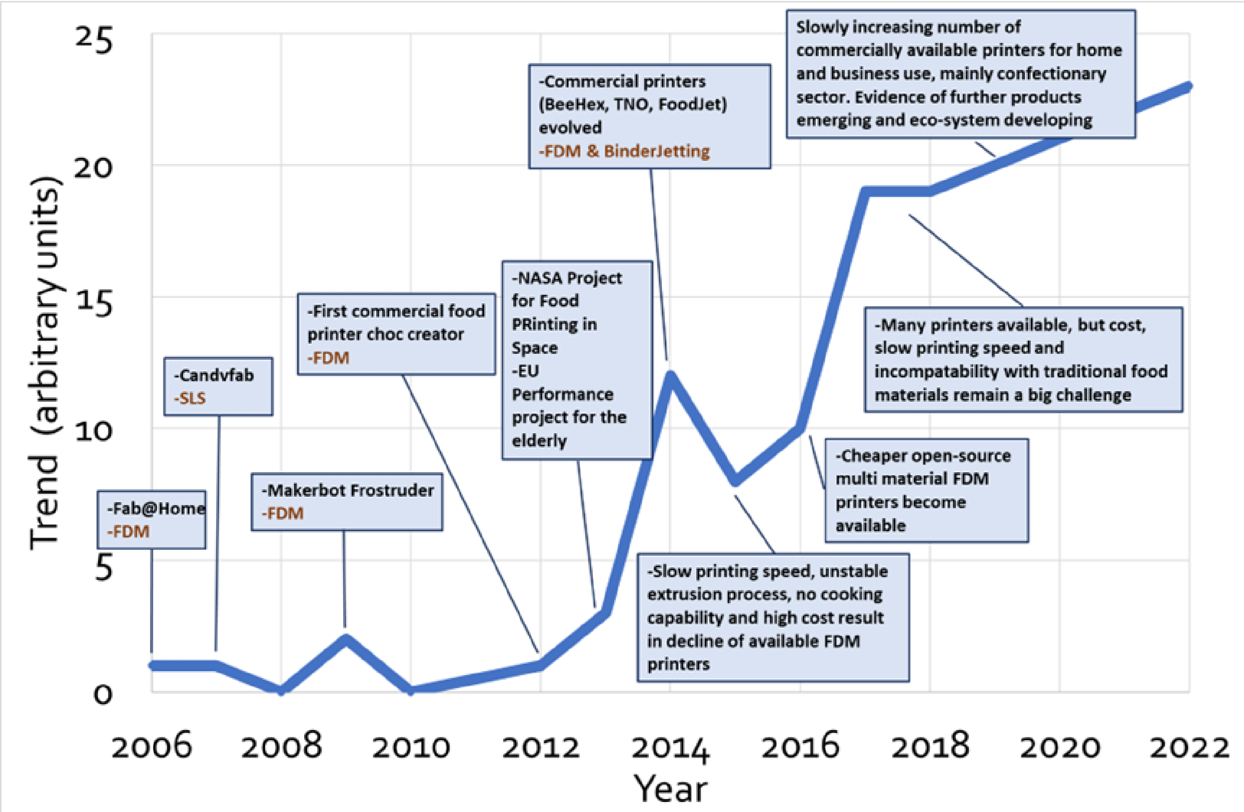

Figure 1: Overview of the temporal evolution of 3DFP (modified from: Agunbiade et al., 2022).

Throughout the mid to late 2000s kitchen appliances producers, such as Electrolux and Philips with its Food Creation Printer translated such concepts by testing the printing of food items from a number of ingredients, stored in cartridges and deposited in layers via a robotic arm, including the development of a graphical user interface that enabled control of ingredient proportions and shapes. The Philips product was presented as market ready in 2008 and gained media attention by being used by a few at the time popular 'molecular gastronomists', without however being developed further to enter wider consumer markets. Around the same time the first patents explicitly proposing additive manufacturing technologies for printing food ingredients were filed (Baiano, 2022; Pérez et al., 2019; Portanguen et al., 2022). The idea of printing food also gained attention as NASA has been exploring food printing concepts for space missions since around 2005 and later launched its 'Advanced Food Technology Program' in 2013 with the aim to make food printing feasible for space travel. However, almost a decade on, several technical issues are still unresolved for space applications (Enfield et al., 2022; Long?zhen Zhang et al., 2022).

Besides appliances manufacturers, prominent academic institutions have been driving technology innovation in food printing conceptually, such as MIT with its Virtuoso Mixer, Digital Fabricator and Robotic Chef (2010), or the Creativemachines Lab at Columbia University where food printing has been explored and tested since 2005 starting with their Fab@Home project and continuing subsequent research, up to recent systems implementing printing devices with integrated cooking functionality using lasers (Creativemachines Lab, 2022; Everett, 2021). Many other academic institutions have over the past decade delivered solutions for specific food ingredients, driving the diversification of specific application areas. For example, University of Exeter (UK) spinout Choc Edge Ltd has developed and commercialised the first UK chocolate printer in 2012 and tested their products for some years, but the company was dissolved in 2021.

After the first technical articles published in scientific journals around 2010, such as the original work on printing chocolate by Liang Hao and co-workers at University of Exeter (Hao et al., 2010), the first widely referenced review articles by pioneers in the field surveying 3DFP research with regards to challenges and opportunities appeared around 2015 (Lipton et al., 2015; Sun et al., 2015; Wegrzyn et al., 2012). At his point, specific opportunities for health applications of 3DFP were explicitly formulated and the first comprehensive text book on the subject has been published in 2018 (F. Godoi et al., 2018; Lipton, 2017). Over the past five years publications have grown almost exponentially (although starting from low numbers, see section 5.1.1) and an industry for producing academic reviews on 3DFP has emerged, sometimes of questionable quality due to repetitive information and a lack of clear research focus and novel insights.

More recently, collaborative networks of academic research institutions and commercial players focusing on 3DFP have emerged. One European example is The Netherlands Organisation for Applied Scientific Research (TNO), which supports development of various innovative food printing applications from plant based meat to healthy products for children and patients as part of the Dutch Digital Food Processing Initiative in a collaboration with Wageningen University & Research and Eindhoven University of Technology. TNO holds patents in 3DFP and has also been involved with developing the 3D pasta printing technology for the Italian pasta maker Barilla, which has since offered 3D printed pasta through its subsidiary BluRhapsody. Other larger research groups conducting fundamental research into 3DFP also exist in the UK, Canada, Spain, Italy, Finland, Germany, Australia and Singapore (see section 5).

1.3 Definition of 3D food printing

The wider definition of 3D printing as technologies that can create 3D objects through a layer-by-layer deposition process using digital image files applies to most 3D printed food items. Definitions in the academic literature mostly focus on the printing process itself defining 3DFP as a process of layered deposition of food ingredients to form edible 3D structures (Baiano, 2022; Derossi et al., 2021; Portanguen et al., 2022). However, one needs to consider that the printing process of food often cannot be separated from the pre- and post-processing steps that are essential for generating the actual food item as shown in figure 2 (Demei et al 2020).

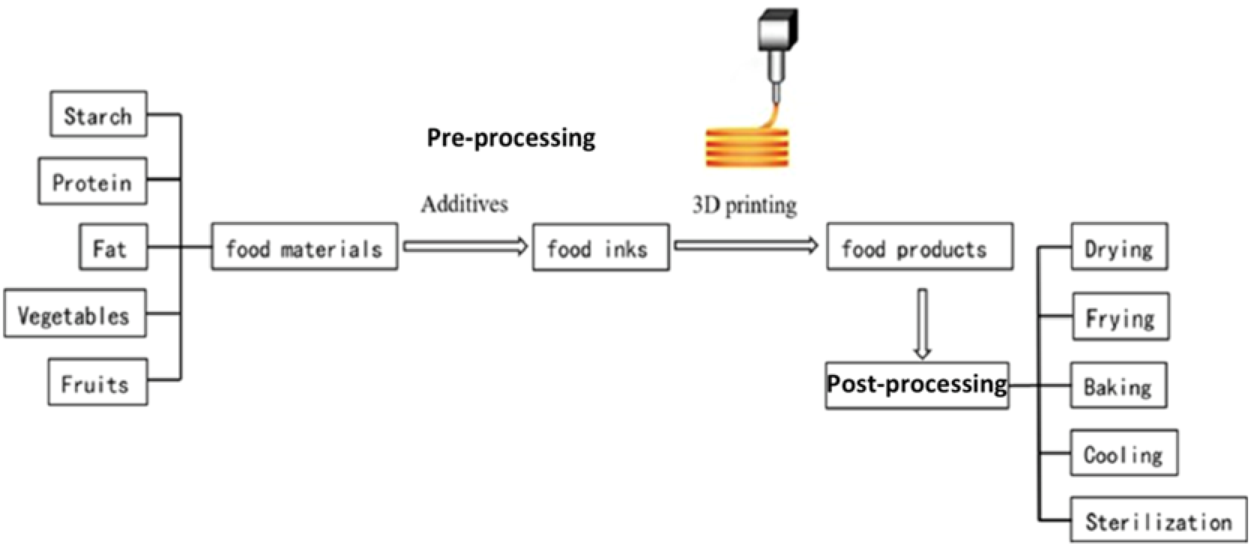

Figure 2: Workflow of a typical 3DFP process using extrusion printing, the most widely used printing technology (modified from Demei et al., 2020)

In contrast to the most common inorganic and organic materials that are used for general 3D printing applications, such as polymers, or metals, the ingredients for food printing are mostly not stable and inert, and can also have a large degree of variation in their material properties, even when using the same recipe (batch to batch variation of food ingredients is a common issue in gastronomy cooking). However, preparing the right ingredient composition for the printer in question is in most cases a precondition for the successful operation of the printer. This is particularly crucial for complex mixtures of ingredients. Likewise, many 3D printed food types require time-critical post processing to make the printed product edible. Hence, in particular from a food safety perspective, it needs to be considered when defining a 3D printed food item whether pre- and post-processing should be considered as integral parts of the printing process, or whether for example final post-processing steps can be completely independent from the printing process, as is the case for example for 3D printed pasta that is frozen after printing and then sold to consumers.

What processing steps are considered intrinsic to the 3D printing process also needs to be clearly defined as currently printing devices emerge that integrate a simultaneous mixing step or a cooking step for example with lasers, or ohmic heating for pre-baking of cake batter while printing (Khodeir et al., 2021). A widening of the definition might also be necessary in order to be able to make distinctions, such as whether specific 3D printed food products would fall into the category of ‘highly processed foods’, or not. Moreover, integrated cooking, or other post processing steps may impact the assessment of 3D printed food with regards to their shelf-life or impact on supply chains etc.

Given these considerations it might be necessary to explicitly include pre- and/or post-processing aspects of the technology in the definition of 3DFP. For the purposes of this report, whenever we use the term 3DFP we mean such a wider definition that could be formulated as:

‘3DFP comprises technologies that can create 3D objects intended for human consumption through a layer-by-layer deposition process using digital files, including pre- and post-processing steps that are essential for producing the final product’.

1.4 Current state of 3DFP - overview

Despite clearly increasing research and commercial activity around food printing over the past 15 years, and in particular the past five years, only a small number of 3D printed food types have matured from the conceptual prototype stage to commercially available and viable products, and most of them only in limited numbers in the context of semi-commercial startup settings, such as chocolate and sugar-based ingredients, food for the elderly and patients with difficulties swallowing, cultured (in-vitro) and plant-based meat, pasta as well as dough-based baked foods, and cheese.

The temporal evolution and scale of technology innovation in 3DFP driven by academic and industry research is well documented in publication and patent data on 3DFP as shown in sections 5.1.1 and 5.1.2 and some comprehensive reviews of the existing literature on 3DFP have been published recently (Baiano, 2022; Derossi et al., 2021; Isabel Diañez et al., 2022; Portanguen et al., 2022). From these sources it is very apparent, that despite some earlier concept development the technology has mainly evolved over the past decade at a small scale and slow pace, with very few active commercial players. Analysis of patent and academic literature data also show that currently only a limited number of food types, mentioned above, are currently printable and technical improvement and process adaptation to different food types is the main concern of most research activity at present.

Very recent innovations, such as 4D printing applications for food in which the texture, colour, taste, or shape of the printed item change over time, or upon external stimuli, are at an early stage and need to become still more robust and cost effective before they might offer added value and can enter wider consumer markets.

However, over the past five years, academic research into the technical possibilities and challenges of food 3D and 4D printing, as well as media reporting on the technology has rapidly increased, and a number of 3D food printers for different types of food, 3D-printed food products as well as service offerings have reached limited consumer and B2B markets (Jayaprakash et al., 2020). In addition, several emerging niche applications for printed food are now specifically promoted by commercial players, such as for printed personalised nutrition, for example Getnourished UK, or for texturizing foods for patients with difficulties eating regular food in hospitals and care homes (Lorenz et al., 2022). 3D printing as a possible solution in this context was already published on the European Commission website in 2014, and research on 3D printing as a technology to improve the eating experience for dysphagia patients in care homes has been tested for example in Germany by government supported research. However, larger commercial operations offering these services at scale are still not on the market.

Despite increasing research and exploration of such potential application areas, 3D and 4D printing of food is at present still a curiosity niche phenomenon, most advanced possibly in the fine dining and confectionery segment for the production of edible and sometimes personalised decorative food items. However, current maturity levels of the few commercially operating food printers, some service offerings on the market, and continuous low-level engagement of large food producers with the technology, are indicative of the potential of 3DFP to be able to reach wider consumer markets via different channels in the future.

1.5 Potential wider impacts of 3D food printing

Anticipating regulatory responses, producers of 3D printers for food have already voluntarily implemented food-compliant industry standards, as for example BASF in Germany has obtained food-compliant TÜV certification for its parts being used in food 3D printers, and food printer suppliers specifically advertise which of their printer parts comply with food grade certification (Molitch-Hou, 2021).

Wider systemic impacts of 3D printing of food are discussed in the academic literature and diversification of the technology into specific sub-niches indicate that 3D printing might act as an enabling or supporting technology for other technology-enabled trends in the food system, such as personalised nutrition, alternative proteins, use of food side- or waste streams (such as in the seafood industry that has in Asia traditionally used seafood production waste for making Surimi paste that can be shaped in different ways and sold as a product in its own right), plant based meat alternatives, cultured meat, functional foods and health nutrition. Moreover, food printing currently appears to be evolving from a focus on the shape aspect of printing towards finding solutions for real food processing challenges and novel ways to for example increase healthy ingredients such as fibre, or reduce salt, sugar and fat intake via printing of specific textures that modify the sensory experience of food, and an area that could be described as food product prototyping (Ma & Zhang, 2022; Portanguen et al., 2022). In addition, some claims about the future potential impacts of 3DFP around its ability to possibly increase sustainability of food production in some cases, or that it might enable business models of decentralised food production affecting supply chain models have been made repeatedly in the academic literature, although without presenting any evidence for these claims (León?Bravo et al., 2019; Verma et al., 2022).

These recent developments indicate that the technology might be entering the food system via different routes and it is therefore important for the FSA to understand potential risks and opportunities of the technology, and in particular whether any regulatory intervention might be required with regards to its remit ensuring that food is safe to consume, food is what it says it is, and food is healthy and sustainable, as stated in the Food You Can Trust FSA Strategy 2022-27. Given the novelty of food 3DFP and its recent dynamic R&D development, the FSA needs to understand what the potential issues of the technology might be with regards to its remit.

1.6 Objectives

This report is intended to assist the FSA in policy development and regulatory decision-making relating to 3D printing of food and food packaging by:

1. Providing an overall assessment of 3D printing technologies as used in the current food system.

This objective aims to explore the current state of 3D and 4D printing technology used in food applications, including 3D printing of food packaging, followed by mapping the potential technological developments on the horizon for the next decade. The findings will be covering both current and emerging research as well as existing applications in the industry.

2. Establishing to what extent developments in 3D and 4D food printing will impact the food system and may act as a catalyst for further change, including shifts in manufacturing and supply of food as well as in consumer trends.

A thorough review of current and emerging technology advances in the context of commercialisation, markets, supply and demand as well as consumer trends will enable identification of wider contexts within the food system that might be of relevance to FSA when assessing impact of food 3D printing on consumers with regards to FSA remit.

3. Establishing implications of 3D printing technologies for food safety for consumers and the food system overall as well as their potential benefits.

Given identified trends and drivers affecting the further evolution of 3DFP, this report will provide an analytical framework and recommendations for the FSA to stay abreast of developments and be able to act when required by designing relevant policy to fulfil its remit.

1.7 Research questions

This report will address a number of relevant research questions to establish the current state of 3DFP, from a technical as well as market and food safety risk perspective, what the trends and drivers and potential future developments of 3DFP may be, and how the technology might affect different parts of the food system and consumers. The current maturity level of 3DFP is at an early stage but has to date generated sufficient evidence to allow an assessment of its potential impact on several aspects of the UK food system. Hence, the following research questions will be addressed:

- What is the current state of the market for the use of 3D printed food items offered by food industry players (service, industry, retail) and what B2B and consumer markets make use of 3D food printers for which purposes?
- What is the state of the technology today, what is its potential over the next 10 years, and which specific markets might have the biggest potential for growth?
- What are the most prevalent offerings and what market segments are they entering?
- How might 3DFP technologies impact the traditional food value chain, and what cross cutting synergies of the technology might impact other trends, such as personalisation of nutrition/food, distributed food production, use of 3D printing in the production of lab-grown meat, or the use of alternative and novel proteins?
- What are potential barriers and contextual factors that may impact adoption and what are technical challenges to the technology?
- What impact might 3DFP have on food safety, and what claims are made by producers about 3D printed food?

- What are the impacts on vulnerable groups, such as patients and the elderly who might be offered 3D printed food in hospitals and care homes without being able to make an informed decision about its consumption?
- What are the potential risks to consumers of 3D printed food packaging, or packaging materials used to package 3D printed foods in line with the above research questions.

1.8 Methodology

This report is based on literature review and standard rapid evidence assessment methodologies used for open access information in academic and grey literature, and no primary research was carried out. The literature review, data gathering and report preparation was conducted in the following phases:

Phase 1: Broad review of academic and grey literature as well as patent databases using custom web search and data analytics tools using a first set of key words and search strings based on the field of enquiry, 3DFP.

The main data source for the initial academic literature search was the Lens database.

Patent searches were conducted using the main IP offices worldwide covering the past 10 years:

- WIPO (patentscope)
- the World Intellectual Property Database
- EPO (Espacenet)
- the European Patent Office
- USPTO, the US full text patent database Additional grey literature was reviewed through researcher-led search

An initial review and analysis of the data was conducted mainly aiming at refining the keywords and search strings

Phase 2: A refined set of keywords and search strings was used to repeat searches. The resulting data was analysed in detail to identify key areas for further research, refine the keywords and search strings further and generate the first data set to be used as basis for human based deep analysis for gap and noise identification

Phase 3: A final set of keywords and search strings was used to conduct searches and the resulting literature was subjected to rigorous researcher-led deep analysis. At this stage, noise was removed from the data, all figures and graphs were generated, reviewed and final outputs produced.

In this way the most relevant literature was identified and used for creating the report content. In addition, relevant social media sites were analysed to get a sense of consumer sentiment and prevalence on the topic of 3DFP. This exercise was not algorithm-based sentiment analysis, but researcher-led analysis on subjects discussed in social media with regards to 3DFP. Throughout the research we benefited from discussions with our expert consultant Dr Lu Zhang, Wageningen University & Research, the Netherlands.

Phase 4: All information was iteratively analysed and verified by different researchers before integration into the draft report. The draft report was sent to both the expert consultant and FSA representatives for review and comments.

Phase 5: Comments and input from both FSA and the expert consultant were considered and addressed. The report was then finalised and prepared in the required format for submission.

Technological foundations of 3D and 4D printing of food

A systematic overview of the technological principles most relevant to the 3D printing of food will be presented and technical specifics of interest for the wider context of the future evolution of the technology will be highlighted. This should enable the FSA to get a baseline understanding of the technical aspects as relevant for its remit.

2.1 General aspects of 3D food printing technologies

Setting up a food printing process requires still considerable effort to adjust parameters and device settings to the exact food type considered, even with commercially available printers already optimised for certain food types. See figure 3 for relevant engineering considerations that are important for setting up a food printing process.

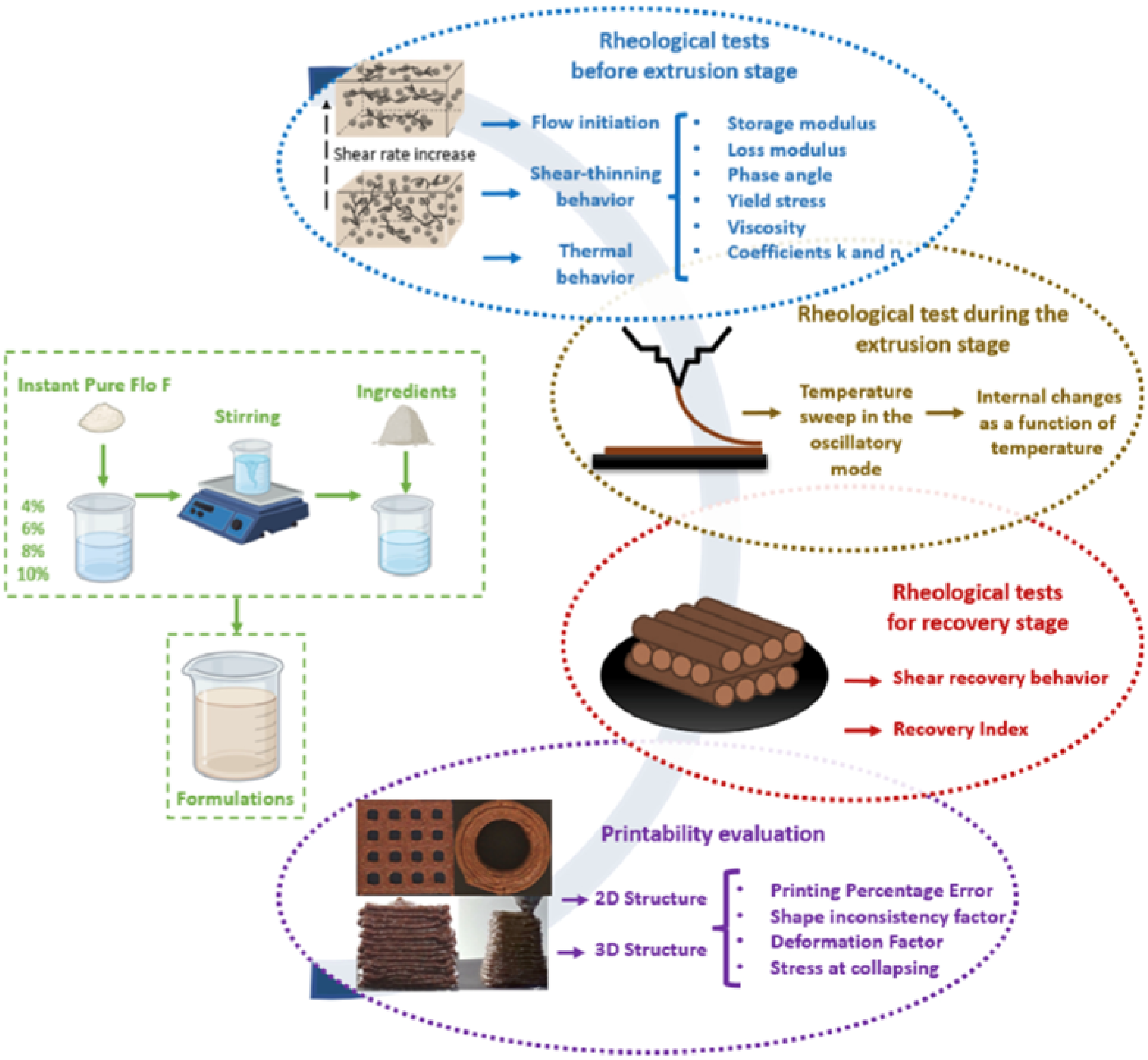

Figure 3: Workflow of engineering considerations important for printing success using an extrusion printing device. Source: Maldonado-Rosas et al., 2022
Rheological tests before extrusion stage:

Shear rate increase

Flow initiation, Shear-thinking behaviour, Thermal behaviour

- Storage modules
- Loss modulus
- Phase angle
- Yield stress
- Viscosity
- Coefficients k and n

Rheological test during the extrusion stage
Temperature sweep in the oscillatory mode
Internal changes as a function of temperature

Rheological tests for recovery stage
Shear recovery behaviour
Recovery index

Printability evaluation

2D Structure, 3D structure

- Printing percentage error
- Shape inconsistency factor
- Deformation factor
- Stress at collapsing

Choosing the best printing methodology for respective food types is crucial for achieving good results. For every ingredient type recipes for ‘food inks’ need to be optimised for the respective printer technology, depending on for example viscosity of food pastes or mesh size of powders, water content etc. (for details see section 3.4). These pre-processing steps can involve automated mixing devices that can be part of the printer mechanism or be independent of the printer, but reproducible and consistent ingredient preparation is essential for printer performance, and incorrect pre-processing can lead to printer failure. In turn, the specific device settings of the printing process need to be established empirically for each food type, for example in extrusion printing with regards to nozzle diameter, printing speed, extrusion rate, layer height and temperature, including adapting to variable external parameters such as room temperature, air humidity etc. (Isabel Diañez et al., 2022). Hence, some printer manufacturers also offer pre-prepared food inks for their printers to ensure quality of consumer printed products. Finally, many printed food items require time-critical post-processing, such as frying, baking, boiling or freezing, which need to be optimised for the food items in question.

Irrespective of the specific printing technology, all current printers require a computer interface that loads and processes 3D image files to communicate user inputs and control commands to the mechanical control unit that drives a form of xyz motorised stage and nozzle arm and other movable parts, such as pumps and mixing screws. The printing process usually involves first model building via CAD software or by scanning a work piece sample, then conversion of the model into a Standard Triangle Language (STL) file that allows building the object layer-by-layer based on x,y,z coordinates, and subsequent robotic execution of STL file commands via G- and M-codes during the printing process creating the 3D object (Baiano, 2022; Guo et al., 2019;

Nachal et al., 2019). It was generally innovations around these aspects of the 3D printing technology that have enabled user friendly interfaces and more robust hardware made specifically for food printing that helped bring down prices for devices so that currently a small range of food printers is available at different price points (see section 5.2 on available printers). In many cases some form of post-processing of the printed object is required, which is usually independent from the printer, although printer developers are working on integrated cooking systems (see section 3.2).

2.2 Types of most common printing principles

Despite the variety of 3D printing systems that exists for other materials, only a limited number have proven to be suitable for printing food, due to the specific physical and chemical properties of food ingredients. We give here a top-level overview of the most widely used printing principles as printed food is exposed to quite different technical environments as well as physical and chemical impacts depending on printer type, which may pose different risks with respect to food safety. At present the following four 3D printing principles are used for food printing, and commercialised printers exist for each of them, although they are not all available for sale. These are: Extrusion-based printing, binder jetting, ink jet printing, and selective laser or hot air sintering.

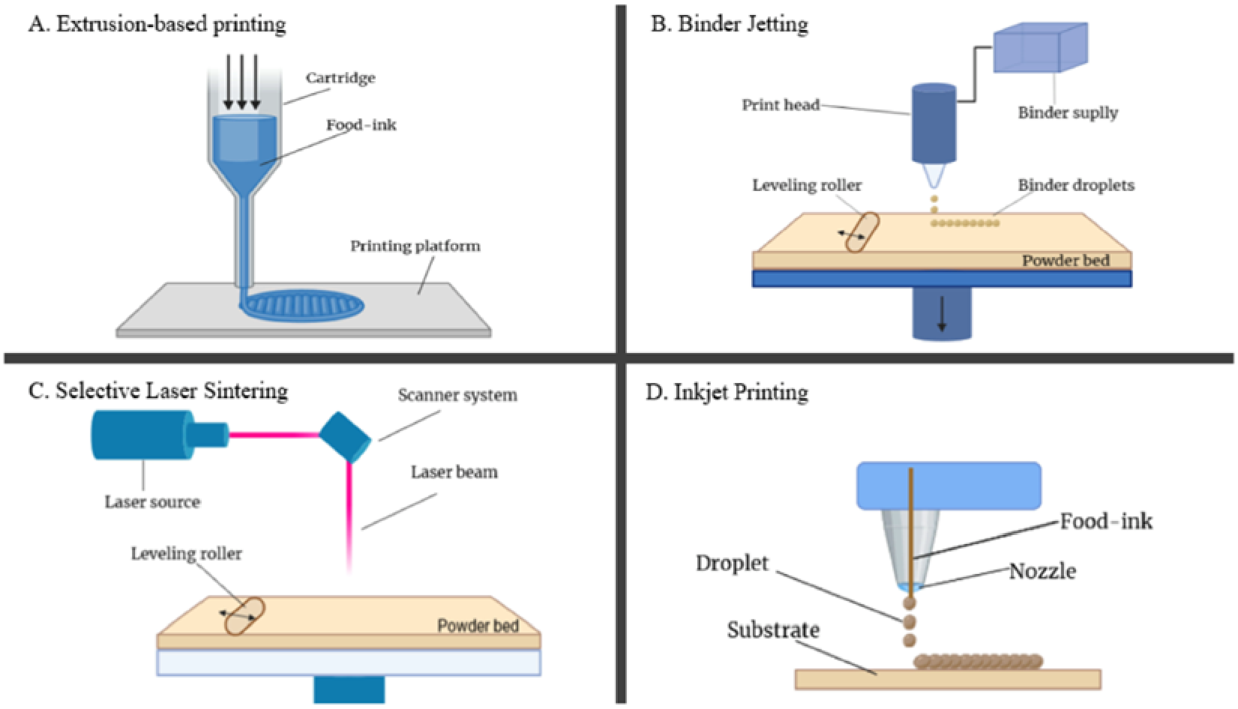

Figure 4: The most common printing principles used for 3D printing of food. Source: Varvara et al., 2021.

2.2.1 Extrusion-based printing

Extrusion printing (fig 4a) is by far the most versatile and most widely applied technique and is based on the extrusion of soft, semi-fluid food pastes, or food inks of a certain viscosity from a cartridge through a nozzle via a pump mechanism. A number of extrusion mechanisms exist but the most common are, syringe-based, air pressure-based, or screw-based.

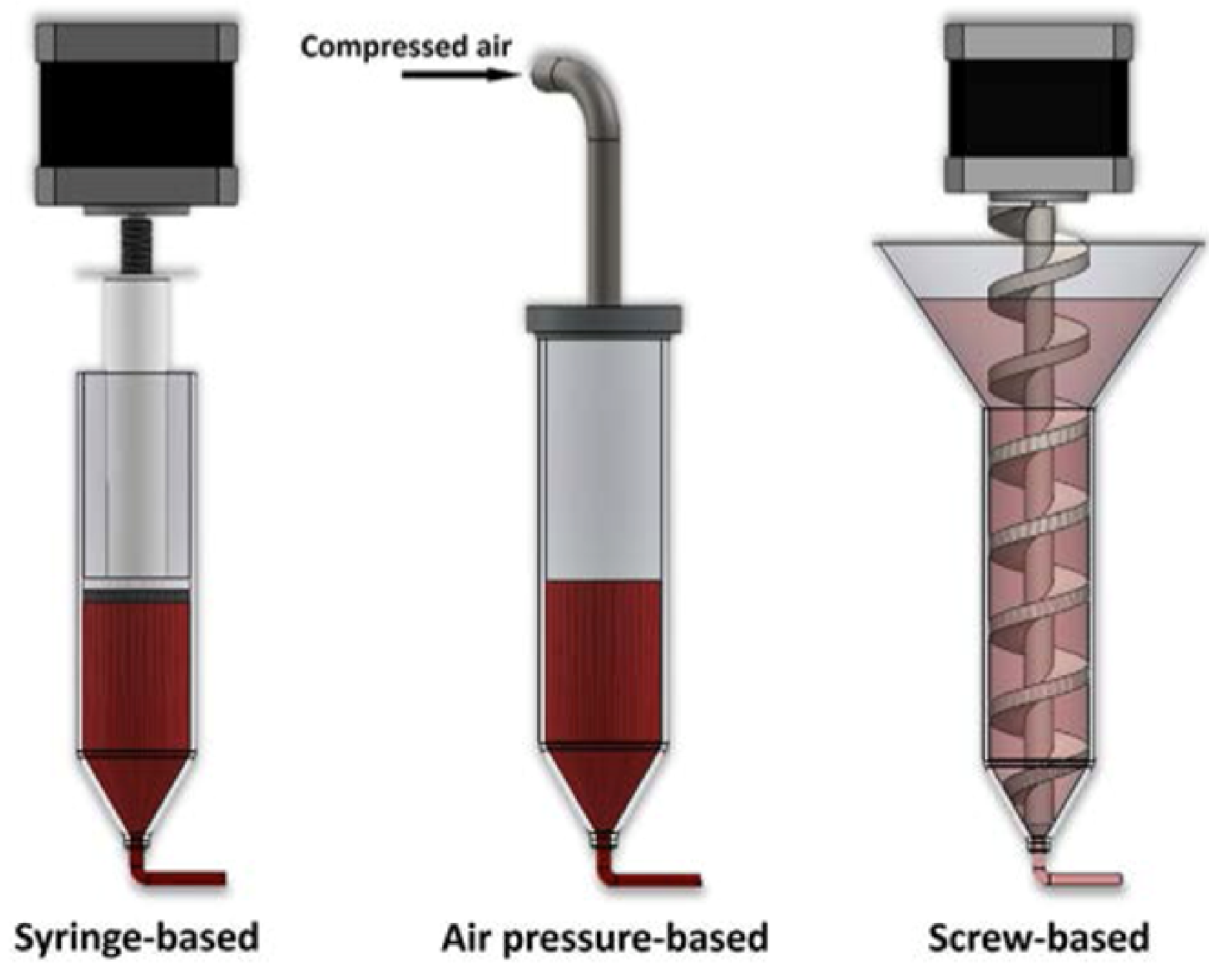

Figure 5: Most common extrusion mechanism used in extrusion printers. Source: Diañez et al., 2022

The final composition and viscosity of food ink can be achieved in some printers by a mixing and dosing system that is part of the printer device and directly delivers the ingredient mixture into the printer cartridge. This process can involve mixing powders, pastes and liquids to produce the desired food ink composition. However the majority of extrusion printers currently require the food ink being already correctly pre-prepared and just loaded into the cartridge.

In most extrusion-based printers the nozzle can be heated to provide optimal flow conditions depending on the temperature-dependent viscosity of the ingredient mixture. Such Hot Melt Extrusion (HME) applications have been used with various materials including many plastics as well as in the pharmaceuticals sector to mix ingredients for medicine formulations (Liu et al., 2017). The 3D structure is deposited onto the printing platform by moving the nozzle in the x,y dimensions and the platform is lowered along the z-axis as the object is deposited layer by layer (or, in some printers the nozzle is moved upwards along the z-axis). With this method for example pre-tempered chocolate, seafood processing waste and meat puree, cheese, different types of dough as well as potato starch-based food items can be printed successfully as well as some fruit and vegetable-based food inks. Several publications have established various ways of optimising extrusion printing parameters for these food items through specific temperature and nozzle control settings and various food additives, such as emulsifiers and thickeners, and a wide range of food standards compliant hydrocolloids (e.g. guar gum, xanthan gum, starch, pectin, gelatine etc.) to achieve a good trade-off between layer bonding, structural stability and reasonable printing speed (Liu & Zhang, 2019; Wilms et al., 2021). The choice of additives for optimising the printing process needs to consider any post-processing steps such as baking, cooking, boiling, microwaving, or frying, as additives affect final consistency and shape of the food product.

Extrusion-based printing is so far the most versatile printing process with the greatest potential for printing also healthy foods as it allows printing of fresh ingredients, such as fruit and vegetables and various ‘functional’ ingredients after addition of the right hydrocolloids, as in principle temperatures can be kept low enough to preserve molecular integrity and nutritional value of such ingredients. Extrusion-based printing is also the method of choice for any personalisation of printed foods due to the ability to control ingredient composition with various precise mixing mechanisms (Ma & Zhang, 2022). Successful printing of meat, plant-based meat and seafood paste (Surimi) and cultured (in-vitro) meat as well as cultured seafood have been reported. For these latter applications it was recommended to keep temperatures below 4C° throughout all printing steps in order to prevent bacterial growth, although no experiments have been carried out to establish specific temperature conditions (Dick et al., 2019; New Food, 2022).

The engineering parameters of extrusion food printing have been studied in great detail over the past decade. For example, a range of extrusion pressures for certain nozzle diameters appears now established for specific food pastes, such as for soft food pastes (e.g. fish, beet puree, egg white foam etc.) with pressures between 20-50kPa, for stiffer pastes (e.g. Marmite) 100-170kPa, or for thicker multi-ingredient protein- and fibre-rich pastes with low water content in the range of 300-600kPa. Also, the engineering parameters of nozzle diameter, flow rate and printing speed are well understood for many food types. Generally, a good trade-off between printing precision, shape stability, and printing speed can be achieved by calculating physical parameters of the material properties of the food inks, such as storage and loss modulus and yield stress, and applying standard engineering equations. However, printing speeds are still slow compared to industrial food production processes and the fastest printers (not yet available for consumer markets) can currently print around 700g of material per minute when printing simple structures (Wilms et al., 2021). Despite the versatility and relative simplicity of extrusion printing, challenges remain around structural stability and long-term printer performance due to the complexity of ingredient mixtures.

2.2.1.1 Types of extrusion-based printing

Within extrusion printing three main printing modes exist, these are non-phase-change extrusion, melting extrusion, and gel forming extrusion (Isabel Diañez et al., 2022; F. C. Godoi et al., 2019).

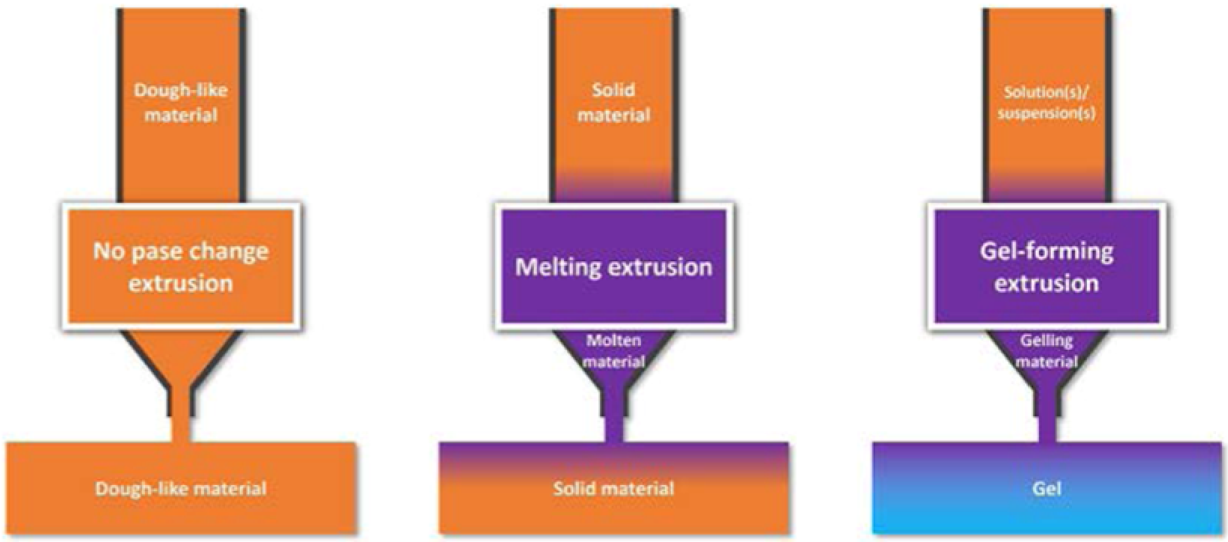

Figure 6: Types of extrusion printing. Source: Diañez et al., 2022

2.2.1.1.1 Non-phase-changing extrusion does not apply any temperature controls, such as heating or cooling, and only relies on the intrinsic rheological properties of the food material, usually at room temperature (fig 4a). This method is often used for doughs such as pasta dough and paste-like ingredients such as purees. However, food standards compliant additives, such as gums or starches are often added to improve printability.

2.2.1.1.2 Melting extrusion is based on the principle used in fused filament fabrication (FFF), which is most common for printing of plastic materials and some metals, involving a heat-induced change of phase during the printing process (usually from solid to liquid to solid). Food ingredients for melting extrusion are often highly viscous or granular pastes that need to be kept slightly above their melting point when in the extruder, but solidify quickly at lower temperatures to obtain the structural stability for the next layer to be built upon (sometimes cooling systems are used to accelerate this process) (Liu & Zhang, 2019). The most common food example for this form of extrusion printing is chocolate, as complex shapes can be generated with this method and a number of commercial chocolate printers based on this principle are, or have been, on the market (Mantihal et al., 2017), for details see section 5.2 and appendix A.

2.2.1.1.3 Gel-forming extrusion depends on the molecular properties of gel forming polymers in solution, which at specific temperatures (gel point) begin to crosslink forming a continuous network usually with large intermolecular spaces that can hold large quantities of the solvent molecules or air, hence forming hydrogels, aerogels, or oleogels. Various gels have been used in the food industry for many decades to modify rheological properties, textures and moisture content of foods and increase shelf life among other applications (Cao & Mezzenga, 2020). Their well researched properties and their role in the food industry have made gels also a prominent ingredient in 3DFP and hydrogels consisting mostly of polysaccharides and proteins are used as an edible base material that can be 'loaded' with various nutrient and taste enhancing ingredients as well as functional molecules. Gels are also extensively studied with respect to their role as a property modifier for improving the printing process for many otherwise difficult to print food ingredients. Many gel types can be loaded into a printer already in their set state, but ideally final gel properties are tuned at gelation point during the printing process which requires optimising temperature, printing speed, layer height and ingredient composition to achieve good results. Gel forming extrusion allows high degrees of standardisation of stable ingredient mixtures before the printing process, also allowing a high reproducibility of printed product, which is one reason why this technique has also found many applications in the biomedical and pharmaceutical sectors (Yan et al., 2018).

2.2.2 Binder jetting

Is a method that uses a binder liquid that is dispensed via the printer nozzle in the x and y axes onto a food powder bed (fig 4b). Upon coming into contact with the powder particles, the binder liquid binds these together producing a solid structure after drying. After each layer is solidified, usually by applying heat to speed up drying, a new layer of powder is applied to the powder bed via a re-coater and the process is repeated after lowering the powder bed table in the z- direction. The method allows for complex structures, reasonable speed, and stability of structures but is limited to relatively homogenous powder ingredients, such as sugar, starch, milk powder, chocolate powder, and hence mostly not suitable for nutritious food items. Binder jetting has found a niche in decorative confectionary items often using food colours, as it also allows for relatively high precision and shape complexity. One example of a binder-jetting printer outside of research laboratories is the CURRANT 3D printer, originally developed by Sugarlabs over ten years ago and possibly coming to the market soon.

2.2.3 Inkjet printing

Is not strictly a 3D method for creating layered structures but rather for dispensing mostly low viscosity food ink droplets onto the surface of food items in a patterned fashion mainly for decorative purposes or surface filling (fig 4d). The nozzle of inkjet printers does not touch the food onto which is printed. Frequently used inks are chocolate, pizza sauce or food-coloured water based food inks, such as sugar syrup. If printing onto food, the physical and chemical properties of the food surface and the ink need to be well considered and printer as well as food ink parameters matched, such that the printed pattern can achieve the desired precision and durability during and after the printing process. The method can be fast, as it is mostly not used for building 3D structures but rather for 2D designs in multiple colours. Examples are PancakeBot , Pancake Printer made by Zbot, China, or Foodjet food printing solutions, the Netherlands, which are advertised as 'food deposition' methods rather than food 3D printing often using large multi-nozzle arrays.

2.2.4 Selective Laser Sintering (SLS) and Hot Air Sintering (HAS)

These are powder-based methods in which the powder particles are melted and re-solidified after being heated (sintered) by either an infrared laser beam (SLS), or a focused beam of hot air (HAS) (fig 4c). After solidification of each layer on the powder bed table, a new layer of powder is applied and the powder bed table lowered along the z-axis. Like with binder jetting, only mixtures of homogenous powders with consistent mesh size of their particles, for example starches with maltodextrin, palm oil powder or sugars and various combinations of such ingredients can be used. Although the method can be fast and generate complex decorative and textural structures, as it often does not require post processing, it is not suitable for fresh or complex ingredient mixtures, as the heat of the laser/air beam are affecting molecular integrity of food ingredients, and the effect of this method on nutritional value of printed items is currently not well understood. Outside research laboratories there are currently no commercialised printers on the market using this technology.

Technology trends in 3D printing of food

Within the technologies currently used for 3D printing of food a number of engineering research and development trends can be observed that mostly aim to optimise certain issues around printing specific foodstuffs. Only after significant technological progress is achieved in these areas will sub-application areas of 3DFP be able to gain commercial viability and enable growth of certain market segments.

3.1 Optimising hardware and processes for different food ingredients

As research into the challenges of 3DFP has increased rapidly over the past five years it has become clear that on the whole 3DFP is still not a robust process for most mixtures of food ingredients and continuous failsafe printing over longer periods of time with consistent high quality results is rarely achievable. Moreover, the size of printable objects is currently limited to a few centimetres in dimension, and with increasing size the complexity of shapes has to reduce considerably. Hence, most novel and experimental food inks are usually printed as simple shapes. The scientific study of the physical and chemical properties of various food ingredients has also shown over many decades that most food ingredients, and in particular mixtures, show a high degree of complexity with regards to chemical, physical, electrostatic and molecular crosslinking properties, which makes exact scientific assessment and prediction of their rheology and printability difficult. Hence, in particular in extrusion–based printing, engineers rely on semi-empirical relations in order to model and predict rheological properties of food ingredients (Wilms et al., 2021). The focus of engineering improvements is mostly on two aspects of the printing process:

1. Product flow during printing, known as extrudability, which is defined by nozzle geometry and extrusion force.
2. Product stability after extrusion, known as buildability, which concerns the rheological properties of the material after printing and its ability to resist deformation when the next layer is deposited.

In order to streamline approaches for improving printability of food ingredients from a hardware and an ingredient formulation engineering perspective an engineering “tool box” approach has been suggested recently that provides a practical starting point for qualitative and numerical analysis and modelling methods that can be applied to optimise printer parts and parameters for different ingredients. This may help the 3DFP field to consolidate empirical approaches and speed up technical developments in the future (Wilms et al., 2021). Besides improving printability, the issue of up-scaling the technology is currently addressed mostly by developing multi-nozzle systems, or by adding more printers in jointly controlled arrangements, such as ‘printer farms’.

Also improvements of printer control through software innovation are expected through the standardisation of applications such as at-line, computer vision based flow rate tracking and developments such as using AI approaches for online adjusting of printer settings during the print run, helping to make 3DFP a more robust technology (Ma et al., 2023). A more detailed presentation of hardware and software engineering approaches is beyond the scope of this report.

3.2 Integrated mixing and cooking functions for extrusion printing

The idea to integrate ingredient mixing devices with shaping and cooking appliances was publicised over ten years ago propagating the concept of ‘digital gastronomy’ that got some media attention at the time, proposing designs for kitchen appliances such as the ‘virtuoso mixer’, the ‘digital fabricator’ and the ‘robotic chef’. However, despite considerable progress in the robotics field over the intervening years, these concepts have not made much progress in delivering commercially viable appliances to the market (Zoran & Coelho, 2011).

Exact proportions of ingredients are not only essential for the success of the 3D printing process, but are also the conceptual foundation of suggested application areas, such as personalisation of nutrients in 3D printed food items. However, in most of the current extrusion based systems, mixing is performed as a pre-processing step independent from the printing system. Liquid/liquid mixing systems, such as the Dicov3ry system made by Structur3D Printing (Canada) have been reported and tested as potentially suitable for integration with food printers, for example to 3D-print fruit-based ingredients, but Integrated mixing systems are currently mostly at the working-prototype stage in research laboratories (Tan et al., 2018; Tomaševi? et al., 2021). Diañez and coworkers have tested successfully a liquid/liquid mixing system of their own design for the printing of oleogels (Isabel Diañez et al., 2022). Despite the fact that liquid/solid mixing is one of the most prevalent processes in cooking and the food industry, well working solid/liquid mixing systems integrated with 3D food printers are still not widely implemented outside of research laboratories, despite their frequent use in pharmaceutical applications. They would open up possibly the largest range of new applications around customisation and personalisation as well as controlled food additives addition, however only a few systems are described or tested with a real-world product. One example was recently published by Diañez and coworkers for the printing of foods for dysphagia patients and shows that innovation in this area is achievable using simple mechanical engineering solutions, however it is acknowledged that integrated ingredient mixing requires still further R&D to deliver standardized products (I. Diañez et al., 2021).

Like with ingredient mixing, integrated cooking during printing instead of separate post-processing of the printed product appears appealing, however, due to the fact that the change in physical and chemical properties of the cooked state mostly interferes with layer building, robust convincing concepts are at present rare. Moreover, one of the main challenges is the fact that controlling heat at a precision that would be required for quasi-simultaneous cooking while printing is very challenging even when using lasers or ohmic heating concepts (Khodeir et al., 2021). Cooking of 3D printed chicken meat paste with blue (for cooking the core) and infrared lasers (for browning the surface) has been tested in the CreativeMachines lab of Prof. Hod Lipson at Columbia University, and Israeli startup SavorEat with its Robot Chef food printer for plant-based meat products that cooks plant proteins during the extrusion process, are to date the most advanced examples of integrated cooking processes with claims to build commercially viable appliances in the future (Everett, 2021).

3.3. 4D food printing

4D printing is a technology that uses a 3D printer to print structures with materials that can change over time (hence 4D), or upon exposure to a physical or a chemical stimulus some time after printing. Material change behaviours in 3D printing were initially mostly explored with regards to shape changes using mainly four principles, self-assembly of elements, deformation mismatch, bi-stability, and shape-memory effects, and a number of technical applications for printed, shape changing structures have been found in areas from biomedicine to construction (Yang et al., 2020; Z. Zhang et al., 2019). 4D printing of food has been explored over the past five years applying the same physical and chemical principles using food ingredients. Apart from changing shape, for example after baking or drying, reproducible change of texture, colour and flavour have been explored with a number of food ingredients (Ghazal et al., 2019, 2021, 2022). To elicit 4D effects, external stimuli, such as contact with water/moisture, heat, light or change of pH etc. need to interact with 3D printed composite mixtures of food materials. Possibly the first 4D printed edible item was a film of a mixture of starch, cellulose, agar and proteins produced at MIT in 2017 that changed shape after contact with water (Wang et al., 2017). Also shape change after drying of 2D printed structures onto edible films has been explored repeatedly, for example by exposing pumpkin paste with different salt concentrations to different temperatures to achieve certain shapes from a flat printed product (fig 7).

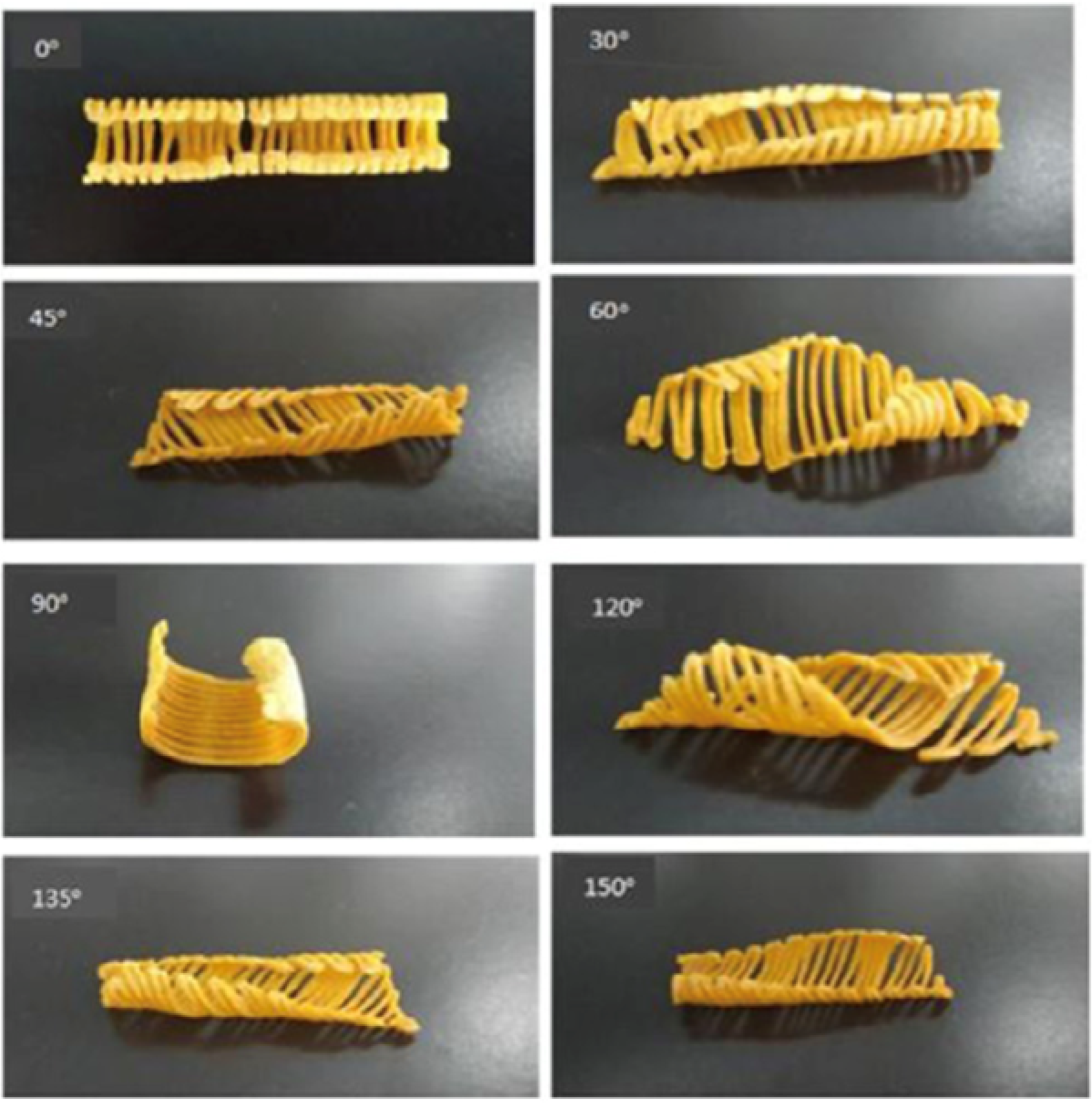

Figure 7: Example of 4D shape change after drying of a flat structure made of pumpkin paste printed onto an edible film. Source: F. Chen et al., 2021

It is usually the combination of ingredients that enables certain change effects, and a limited number of studies added natural colour changing molecules, or aromatic molecules that change flavour upon certain stimuli to a printable base material. Colour and aroma change has for example been explored in a mixture of mashed potato and purple sweet potato puree, lotus root powder gel, and anthocyanin-potato starch gel, after microwave heating and change of pH (Chen et al., 2021; C. He et al., 2020), and in buckwheat/yellow flesh peach dough in combination with edible gelatine gum-arabic-oil complex coacervates microcapsules, containing (E)-cinnamaldehyde as the (cinnamon) aroma. After microwave heating a two-fold increase of cinnamon aroma was reported (Guo et al., 2021). Ethyl cellulose has recently been tested as an additive for 4D printing applications due to its potential as a shape and colour change enabling ingredient as well as a number of natural ingredients that change flavour or colour upon change in pH (Navaf et al., 2022; Pulatsu et al., 2022).

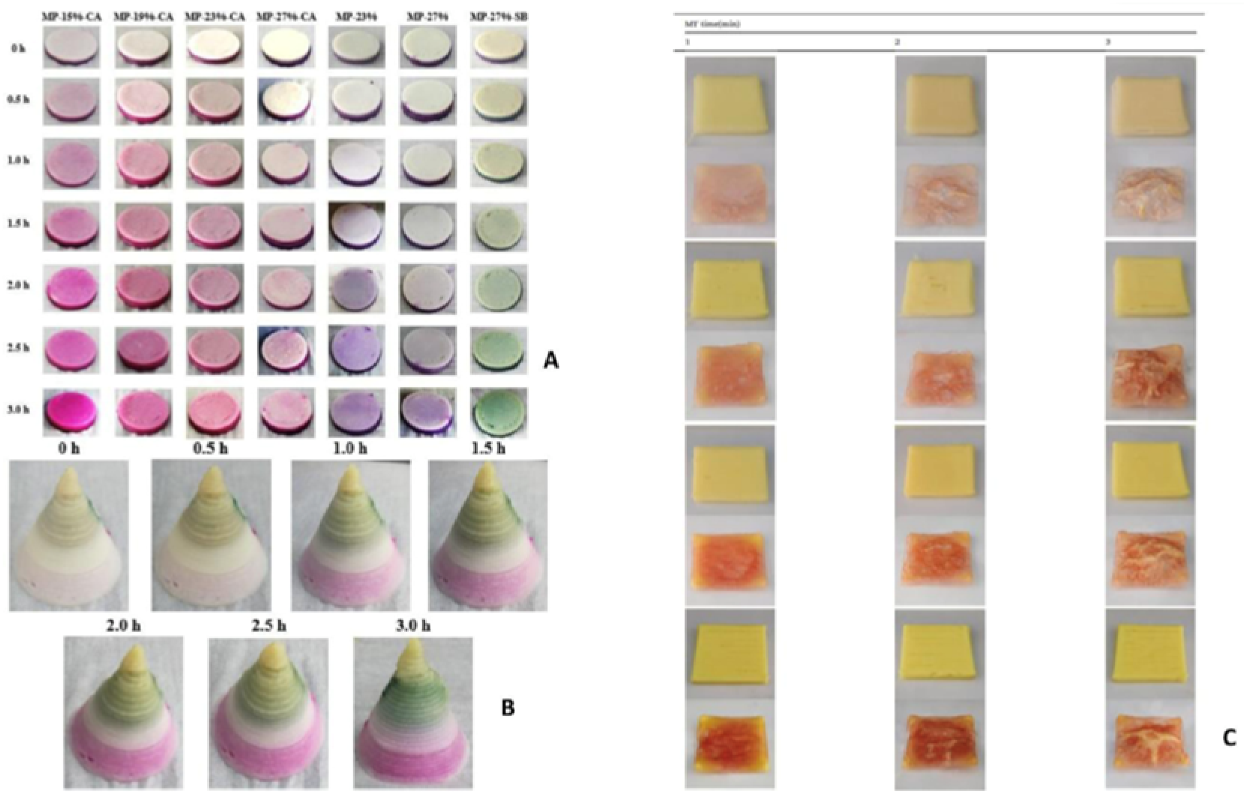

Figure 8: Examples of colour change after a change in pH (A, B), and shape and colour change after microwave heating (C). Source: Oral et al., 2021.

Although some of the shape change effects of 4D food printing rely to some extent on a 3D printer, other 4D effects, such as change of colour or flavour are based on well understood principles of food chemistry and do not necessarily depend on a 3D printing process. 4D food printing is still at an experimental phase looking for applications beyond curiosity markets. More research in this area may also provide input into solutions for making timed and stimulus-induced changes of food materials a part of food safety monitoring applications. At present 4D food printing is happening mostly in research laboratories and scalability and commercial viability of the explored concepts need to be tested still. Some of the effects studied may find applications outside of 3DFP (Navaf et al., 2022).

3.4 Novel food inks

Since the focus of 3DFP research has shifted in recent years from the shape aspect of printed products in the form of decorative elements mostly printed with chocolate or sugar-based ingredients to healthier ingredients, efforts to develop novel food inks that have explicit health benefits have rapidly increased. However, experimentation with the formulation of food inks based on ingredients of specific nutritional value has shown that these are often difficult to print without additives, hence finding the right combination and proportion of additives that does not affect the ‘healthiness’ of the printed food product is of considerable interest to researchers in the field. Other ‘health enhancing’ effects that might be achieved through 3D printing are based on specific textures that can be achieved with 3D printing and are discussed in the next section.

Desired nutritional enhancements of 3D printed foods are often an increase of protein content in applications such as snack bars, or of ingredients with health benefits, such as fibre or fresh vegetables, which all still pose considerable challenges with respect to printability. A number of proteins have been tested for making protein-rich 3D printed snacks, such as milk protein, whey protein, sodium caseinate, and various plant proteins, such as soy, pea, and bean proteins, mostly by extrusion printing. Binder jetting was used recently successfully to print high protein content structures with a mixture of calcium caseinate powder, starch and medium-chain triglyceride (MCT) powder (Zhu et al., 2022).

This printing method allows for high dry mass content and greater speed and complexity of shapes than extrusion printing. Snacks rich in fibre and protein have been successfully printed using mixtures of various milk and bean proteins including cellulose micro-fibres (Lille et al., 2018). Moreover, as interest in alternative sources of protein for human consumption has increased in recent years the use of insect proteins, such as mealworm powder, and proteins from algae have been tested successfully for 3DFP applications (Azzollini et al., 2018; Bedoya et al., 2022).

Printing with fresh ingredients, such as vegetable purees, has been tested and was anticipated as a way to incentivise children or patients with swallowing difficulties to eat more vegetables. For example, fresh peas, carrots and bok choi with minimal hydrocolloid additives (such as xanthan gum, kappa carrageenan or locust bean gum) could be printed successfully via an extrusion printer (Pant et al., 2021), see figure 9. The Dutch company Gastronology has recently announced to currently up-scale operations and that they plan to be on the market for hospitals and care homes soon with frozen [3D printed foods made from vegetables](#).

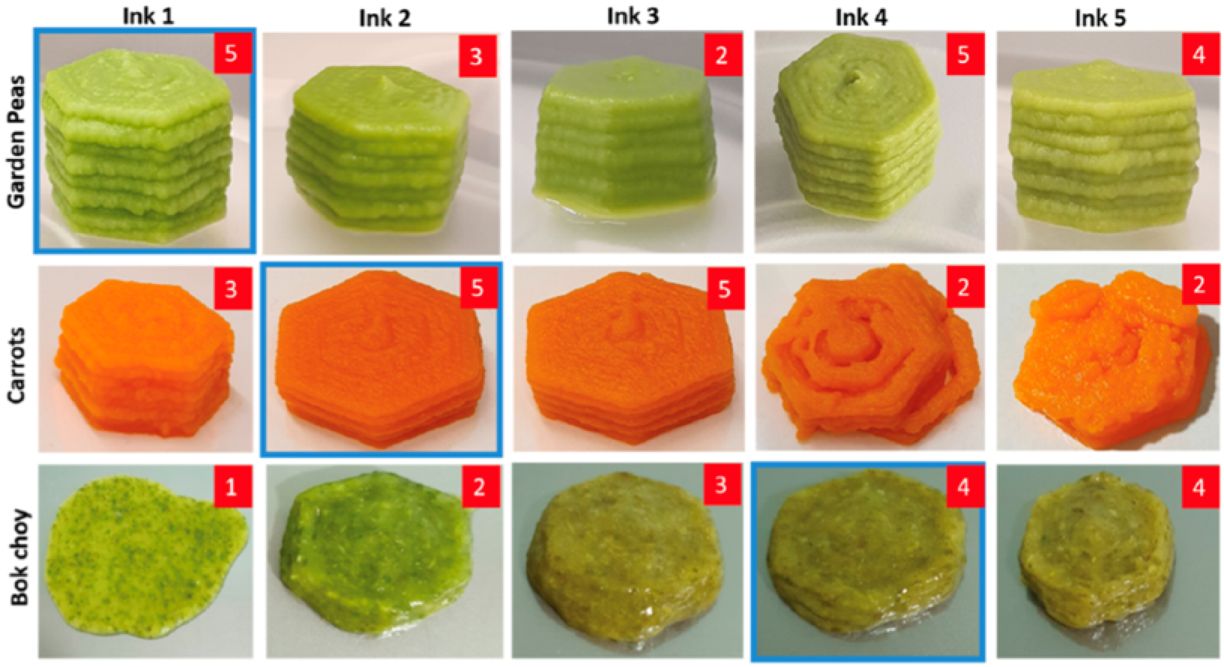

Figure 9: Examples of 3D printed food based on vegetable ingredients (numbers indicate score for shape and print fidelity). Source: Pant et al., 2021.

Other vegetables such as potatoes, mushrooms, yam, spinach and broccoli have been tested either from fresh or from freeze-dried powders with variable success, and some additives, such as starches and gums or gelatine, have to be used in most cases in order to enable printability. Also fruits, such as mango, kiwi, orange, lemon, strawberries have been studied and can be printed mostly with gel-forming printing processes that require the addition of some gelling agent, such as various types of starch or gelatine. 3D printed protein-fortified lemon-based gels have been tested in care homes in a small trial in Denmark (Chow et al., 2021; Waghmare et al., 2022). With respect to adding 'health enhancing' ingredients that would turn 3D printed food items into 'functional foods' a number of natural bioactive molecule classes, such as carotenoids, polyphenols, vitamins, unsaturated fatty acids and probiotics among others have been studied for their suitability for addition into healthy food inks and for their compatibility with the 3D printing process (Donn et al., 2022; Lu Zhang et al., 2018). Adding such functional molecules does not strictly require a 3D printing process to produce functional foods, however, depending on what type of functional molecule is added, mostly without affecting printability, specific claims can be made about the printed food, such as for example that 3D printed food could help with reducing oxidative stress or positively affect inflammatory conditions, positioning such 3D printed foods close to nutraceuticals, although such claims are still rare (Cotabarren & Palla, 2022). For printing more complex products that combine different nutritional benefits, for example high protein with high fibre content, a number of combinations of proteins and fibre types, for example fava bean extraction fractions, or whole milk powder and wholegrain rye flour have been successfully tested with regards to printability (Johansson et al., 2022; Lille et al., 2018, 2020).

These attempts to find formulations for healthy 3D printed products are still facing many technical challenges, in particular with standardisation and scale-up of recipes, although first attempts to enter niche markets with such health focused 3D printed products are reported to happen possibly in the near future, as mentioned, for example in the Netherlands. Despite various proposed health claims, the actual scientific assessment, and agreement by regulators what needs to be measured to make these claims valid for 3D printed foods is at present still lacking (as for many other foods that are sold with such claims).

3.5 3D food printing for texturising and sensory modification of foods

Textures are as important as flavours in characterising authentic whole foods and 3D printing has in the past five years been explored as a tool to manufacture specific textures as well as for prototyping the sensory experience aspect of certain foods. These attempts were motivated largely by three objectives with consumer products in mind, namely to achieve dietary change by modifying sensory experience, to create microstructures that can mimic natural textures, for example in the plant based and in-vitro meat sectors, and to provide texturised foods for patients with swallowing difficulties.

3.5.1 Dietary objectives

A change of sensory or taste experience was achieved for example by changing infill pattern and infill density of 3D printed foods to change sensory perception in order to create the “sensory illusion” of greater sweetness or saltiness, despite less salt or sugar being used with the ultimate aim to help consumers reduce these ingredients in their diets (Fahmy et al., 2021; Zhu et al., 2020). Also the contribution of microstructure and resulting chewiness in connection with the sensation of satiety, have been explored (Lin et al., 2020). These 3D printing applications may in the future also serve as exploratory tools for food product design and prototyping, rather than being used as production methods.

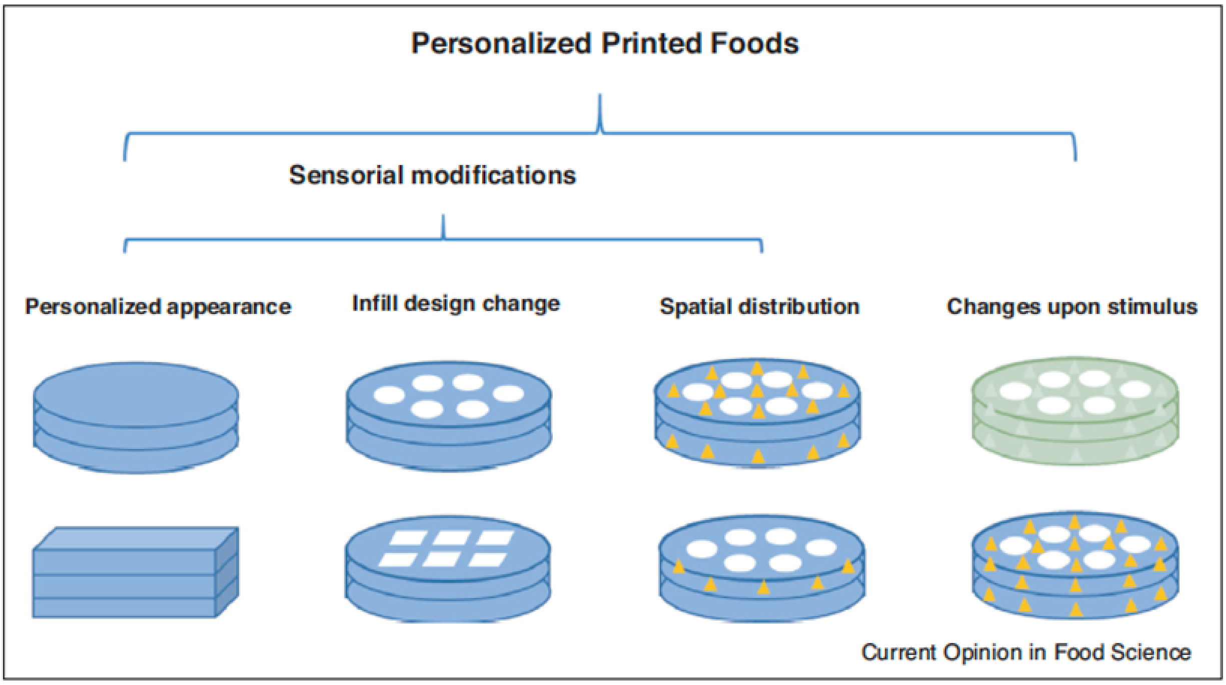

Figure 10: Examples of textural design concepts for sensory modification using 3D and 4D printing. Sensory experience can be changed with different infill patterns and spatial distribution of ingredients, including 4D effects upon external stimuli. Source: Ma & Zhang, 2022.

3.5.2 Mimicking natural textures

One of the initial weaknesses of the plant-based and cultured meat alternatives products has been a lack of convincing texture. After initial experimentation with the addition of 'texturizing' ingredients into the ingredient mix both plant based and cultured meat alternative producers have in the last three years started to use 3D printing approaches to texturise their products (K. Handral et al., 2022). One of the successful plant-based meat companies in Europe, Novameat, Spain, has developed standard 3D printing technology further into a patented micro-extrusion appliance that can generate meat like textures. Likewise, Steakholder foods, formerly MeaTech 3D, Israel, use a modified 3D printing approach for the same purpose to produce their cultured meat products including more recently fish. Revo foods, Austria, (formerly Legendary Vish) use allegedly 3D printing to produce plant-based seafood products with their salmon products already available in some Austrian supermarkets as well as through local delivery services. They use pea proteins, algae and plant oils as ingredients, making their products a source of omega 3 oils. Revo has recently allegedly entered markets in 20 countries including the UK and signed contracts with REWE, one of the largest food retailers in Europe (Vegconomist, 2022a, 2022b). However, industry insiders doubt that the used technology would strictly classify as 3D printing.

3.5.3 Creating textured food for dysphagia patients and the elderly

Texturising foods with 3D printers for patients with swallowing difficulties due to neurodegenerative and other illnesses, called dysphagia has been explored by a number of researchers (Kouzani et al., 2017). Limited real-world tests have been carried out meanwhile, also driven for a while by an EU project titled: Personalised Food for the Nutrition of Elderly Consumers (PERFORMANCE) that started already in 2014 coordinated by the German company Biozoon Food Innovations, and the German government has supported research into testing such products in care homes. However, updates or publications on outcomes from this initiative are not available at present. Textures produced for dysphagia patients via 3D printing, using vegetable and meat based ingredients have been shown to fulfill food consistency requirements of the

International Dysphagia Diet Standardization Initiative (IDDSI), framework and the state of the art of 3D printing for dysphagia patients has been reviewed very recently (Liu et al., 2021; Lorenz et al., 2022). Like other advanced applications for food printing, printed food for patients or the elderly is currently not available beyond a few small proof-of-concept trials that have been carried out in the past few years.

Trends, drivers, and barriers shaping the 3DFP market

A number of potential drivers and challenges for the future evolution of 3DFP were identified in the course of this research. These range from specific R&D activities in research laboratories, the current conditions in the food printer hardware market and related business models, to certain consumer trends and commercial developments that all may influence to what extent the technical potential of 3DFP may lead to viable solutions in the food system in the future.

5.1 3D food printing R&D, academic literature and patenting

To get an overview of trends in the academic literature and patent space we have used customised data analytics tools to capture baseline trends in the evolution of R&D activities related to 3DFP.

Recent reviews of varying quality have looked into the publication evolution of the field (Agunbiade et al., 2022; Baiano, 2022; Derossi et al., 2021; Portanguen et al., 2022). For example, Portanguen and co-workers have used the Science Direct database for their analysis, as shown in figure 11.

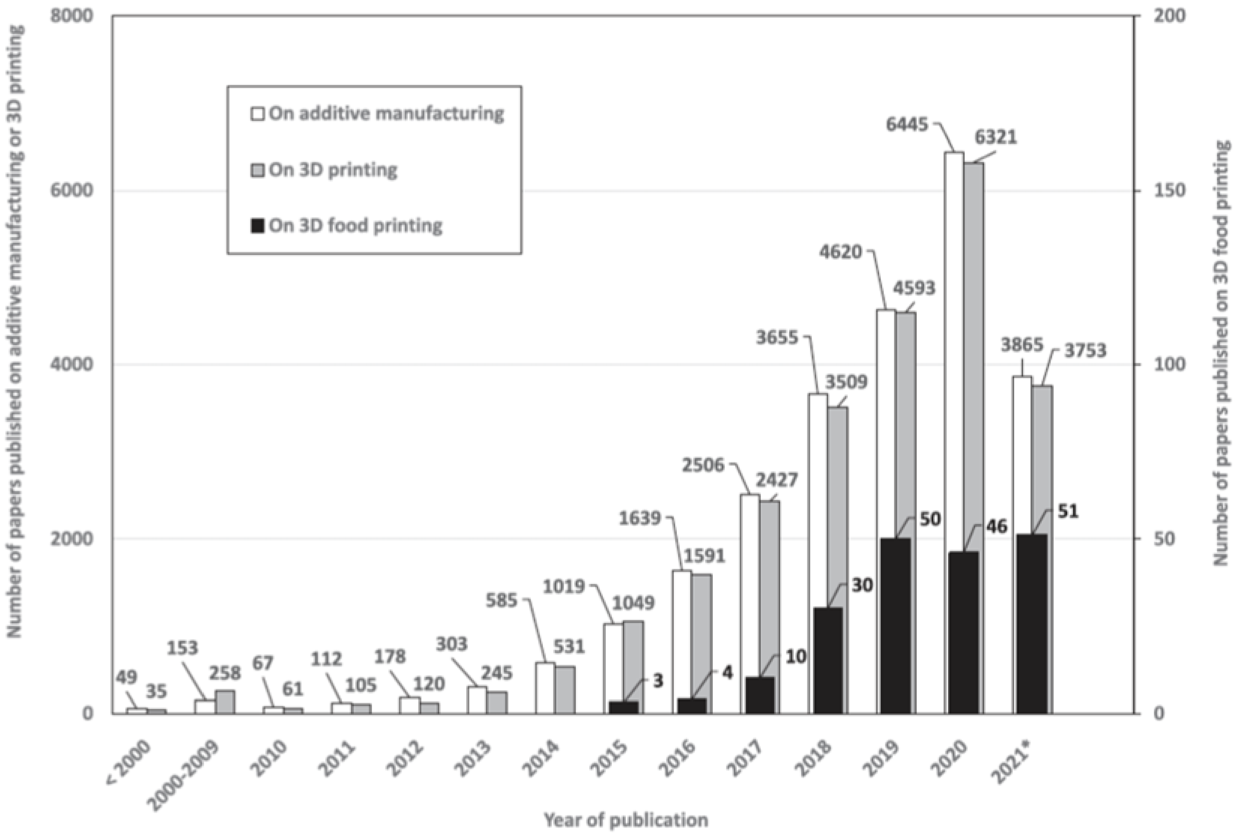

Figure 11: Publication evolution of the academic literature on 3DFP compared with literature on additive manufacturing and 3D printing. Note incomplete data for 2021. Source: Portanguen et al., 2022.

These recent reviews report consistently low numbers of publications, and although absolute numbers vary depending on search strategy and databases used, authors concur that the field of 3DFP has mostly emerged within the past 15 years with a rapid increase in research output over the past five years.

In order to update information and to use an approach that allows for a wider search horizon we have performed literature analysis in the LENS database, for details see methodology section.

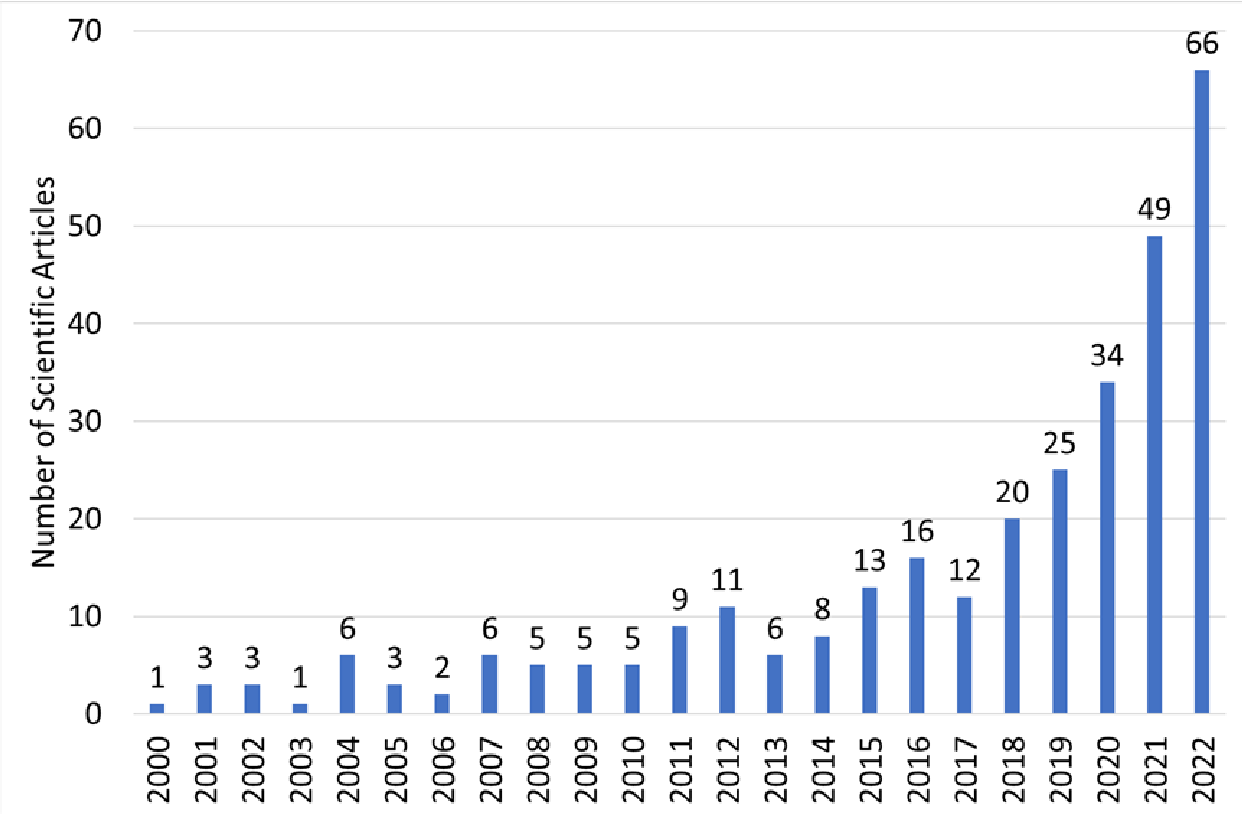

Figure 12: Evolution of the academic literature on 3DFP over the past two decades. Analysed in the LENS database using less stringent search criteria. Note: data from 2022 incomplete (up to 25. November).

This search was carried out in two steps, first applying an algorithm-based approach to cover breadth of sources, followed by researcher based critical review of the data that narrowed down the search to the most relevant data since 2015, yielding a total of 103 publications in peer reviewed journals (fig 13).

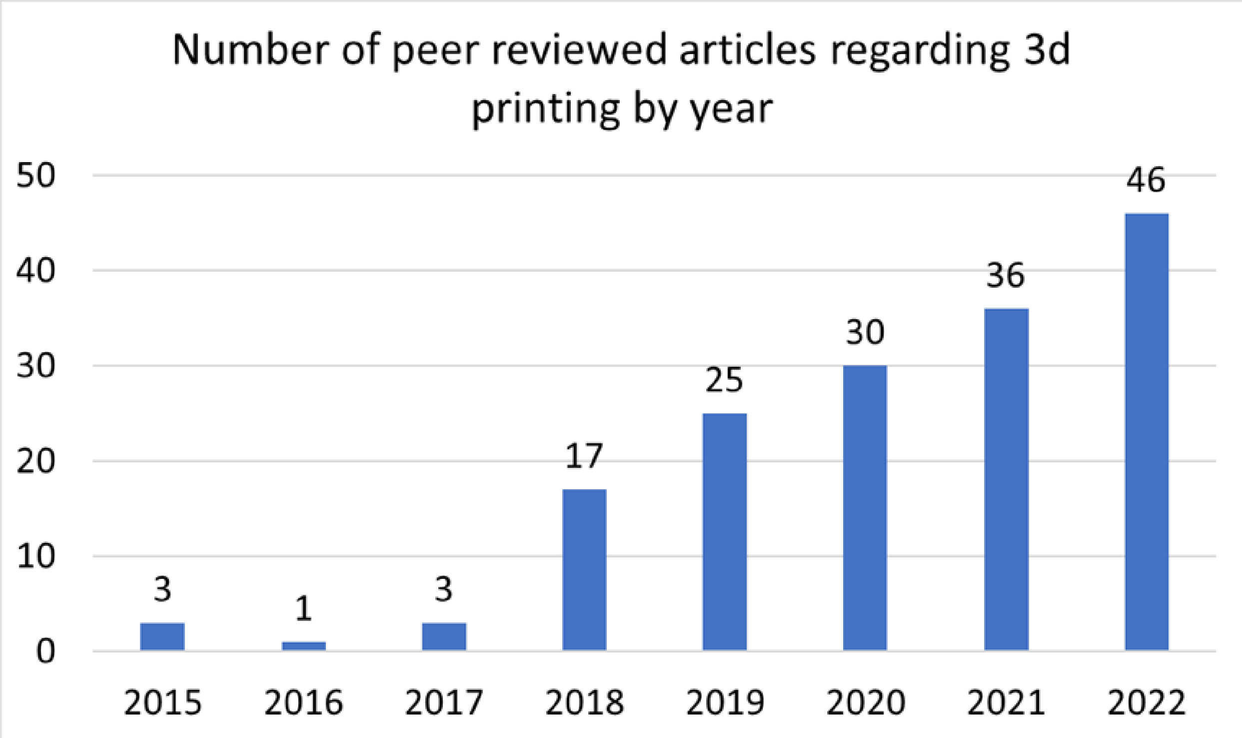

Figure 13: Number of peer-reviewed publications directly relevant to 3DFP. Note: data for 2022 up to November 30.

We can confirm that 3DFP as an academic research field is small, rapidly expanding over the past five years and dominated by a few productive authors that are referenced by a number of the most recent publications, magnifying their impact although this does not necessarily reflect the quality and impact of research work on the progress of the field.

Table 1: Most published authors in the 3DFP literature and their affiliations

Author	Number of publications	Affiliation	Country
Min Zhang	30	Jiangnan University	China
Bhesh Bhandari	24	University of Queensland	Australia
Sangeeta Prakash	11	University of Queensland	Australia
Maarten A.I. Schutyser	7	Wageningen University	NL
Arun S. Mujumdar	6	McGill University	Canada

Author	Number of publications	Affiliation	Country
C. Anandharamakrishnan	5	Food Engineering Department CSIR -CFTRI Mysore	India
Chaohui Yang	5	Jiangnan University	China
Jeyan A. Moses	5	National Institute of Food Technology, Entrepreneurship & Management - Thanjavur | NIFTEM-T India	India
Lu Zhang	5	Wageningen University	NL
Pattarapon Phuhongsung	5	Jiangnan University	China
Zhenbin Liu	5	Jiangnan University	China
Chaofan Guo	4	Jiangnan University	China
Javier Martínez-Monzó	4	Universitat Politècnica de València	Spain
Markus Stieger	4	Wageningen University	NL
Purificación García-Segovia	4	Universitat Politècnica de València	Spain
Sakamon Devahastin	4	King Mongkut's University of Technology Thonburi	Thailand
Sicong Zhu	4	Wageningen University	NL
Sylvester Mantihal	4	Universiti Malaysia Sabah	Malaysia

Research institutions outside of China with a strong focus in 3DFP are for example University of Queensland in Australia, McGill University in Canada, and Wageningen University in the Netherlands. Also Spain has not only two active universities carrying out research on 3DFP, but also a well-networked ecosystem of 3D printing technology developers in the Barcelona region leading to important synergies. When looking into the most researched food items investigated by these most published authors it becomes clear that many are exploring novel ingredients that have traditionally not been printed before, such as vegetable and fruit based ingredients, or microalgae and various proteins and fortifying ingredients, such as vitamins and probiotics (table 2).

Table 2: Food ingredients studied by the most published authors in the 3DFP field

Author	Number of publications	Affiliation	Country	Foods
Min Zhang	30	Jiangnan University	China	Mashed potato, lemon juice gel, steak-like using soy protein, rose-sodium alginate, Nostoc sphaeroides biomass
Bhesh Bhandari	24	University of Queensland	Australia	Mashed potato, dark chocolate, Vitamin-D Enriched Orange Concentrate, steak - like (soy protein)
Sangeeta Prakash	11	University of Queensland	Australia	Chocolate, surimi, food for dysphagia patients, egg white protein, layered beef
Maarten A.I. Schutyser	7	Wageningen University	NL	Chocolate, sodium caseinate - sodium alginate blends, microalgae-enriched 3D-Printed Snacks

Author	Number of publications	Affiliation	Country	Foods
Arun S. Mujumdar	6	McGill University	Canada	Potato gel, fermented dough
C. Anandharamakrishnan	5	Food Engineering Department CSIR - CFTRI Mysore	India	Indigenous composite flour, chicken nuggets, encapsulated probiotics
Chaohui Yang	5	Jiangnan University	China	Vitamin-D enriched orange concentrate, mashed potato/strawberry gel
Jeyan A. Moses	5	Nat. Inst. of Food Tech - Thanjavur	India	Composite flour, chicken nuggets
Lu Zhang	5	Wageningen University	NL	Microalgae-enriched 3D-printed snacks, personalised bakery products
Pattarapon Phuhongsung	5	Jiangnan University	China	Composite mixture of soy protein isolate, pumpkin, and beetroot, fermented dough
Zhenbin Liu	5	Jiangnan University	China	Mashed potato, shiitake mushroom for dysphagia diet
Chaofan Guo	4	Jiangnan University	China	Nostoc sphaeroids biomass, lemon juice gel

Author	Number of publications	Affiliation	Country	Foods
Javier Martínez-Monzó	4	Universitat Politècnica de València	Spain	cookies, gluten free dough, mashed potato
Markus Stieger	4	Wageningen University	NL	Protein bars, chocolate coated rice waffles (for sensory study), sodium caseinate - sodium alginate blends
Purificación García-Segovia	4	Universitat Politècnica de València	Spain	cookies, gluten fee dough, potato cookies
Sakamon Devahastin	4	King Mongkut's University of Technology Thonburi	Thailand	Ergosterol-incorporated purple sweet potato pastes, surimi, mixture of soy protein isolate, pumpkin, and beetroot
Sicong Zhu	4	Wageningen University	NL	3D printed protein bars, sodium caseinate - sodium alginate blends, chocolate coated rice waffles (for sensory study)
Sylvester Mantihal	4	Universiti Malaysia Sabah	Malaysia	Chocolate

Using text analysis tools, the frequency of various research topics can also be visualised to give an overview of the whole of the publication space.

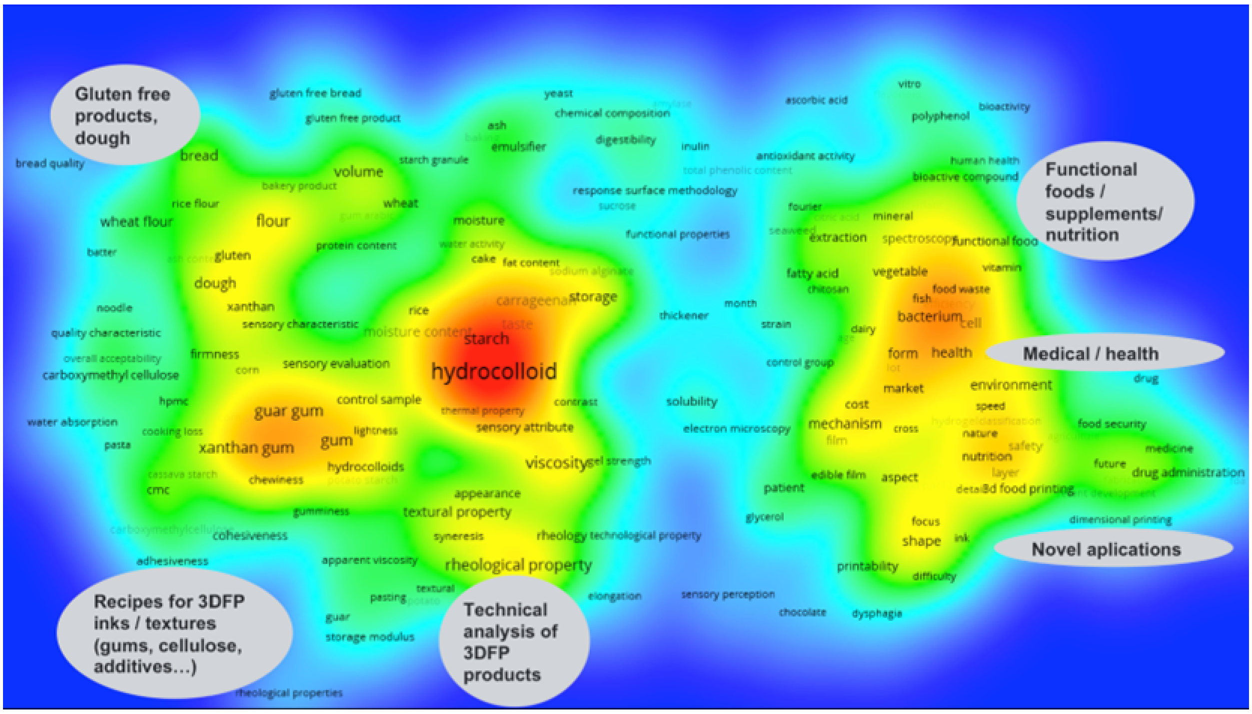

Figure 14: Word frequency landscape visualising topic areas in the 3DFP literature.

Visualisations like this show for example that most of the literature is concerned with the technical aspects of formulating printable food inks and optimising printing conditions using hydrocolloids (such as different types of starch and gums (centre left, and left) to improve printability), indicating that additives are essential for 3DPF to enable the technical printing process, and physical and chemical characterisation of viscosity/rheology of food inks is a major technical research concern (lower centre). This also highlights that extrusion-based printing is the dominant technology, and that binder jetting or selective laser sintering are very much niche technologies within the field. It also shows that some food types are intensively researched for 3D printability, such as dough/flour-based products (top left), reflecting also the fact that commercially available printers for these products exist for some years. Other areas of research that have emerged more recently, are seen in the cluster on the right, with a focus on health and specific nutritional requirements and emerging, proposed application areas.

When looking into the evolution of specific food types that have been researched for 3D printing it also becomes clear that these are still very limited, as for example a timeline graph of the number of publications mentioning specific printed food types shows (figure 15). It also shows that the most recent research on printability of vegetables, fruits or proteins has not yet had sufficient impact on the field as a whole.

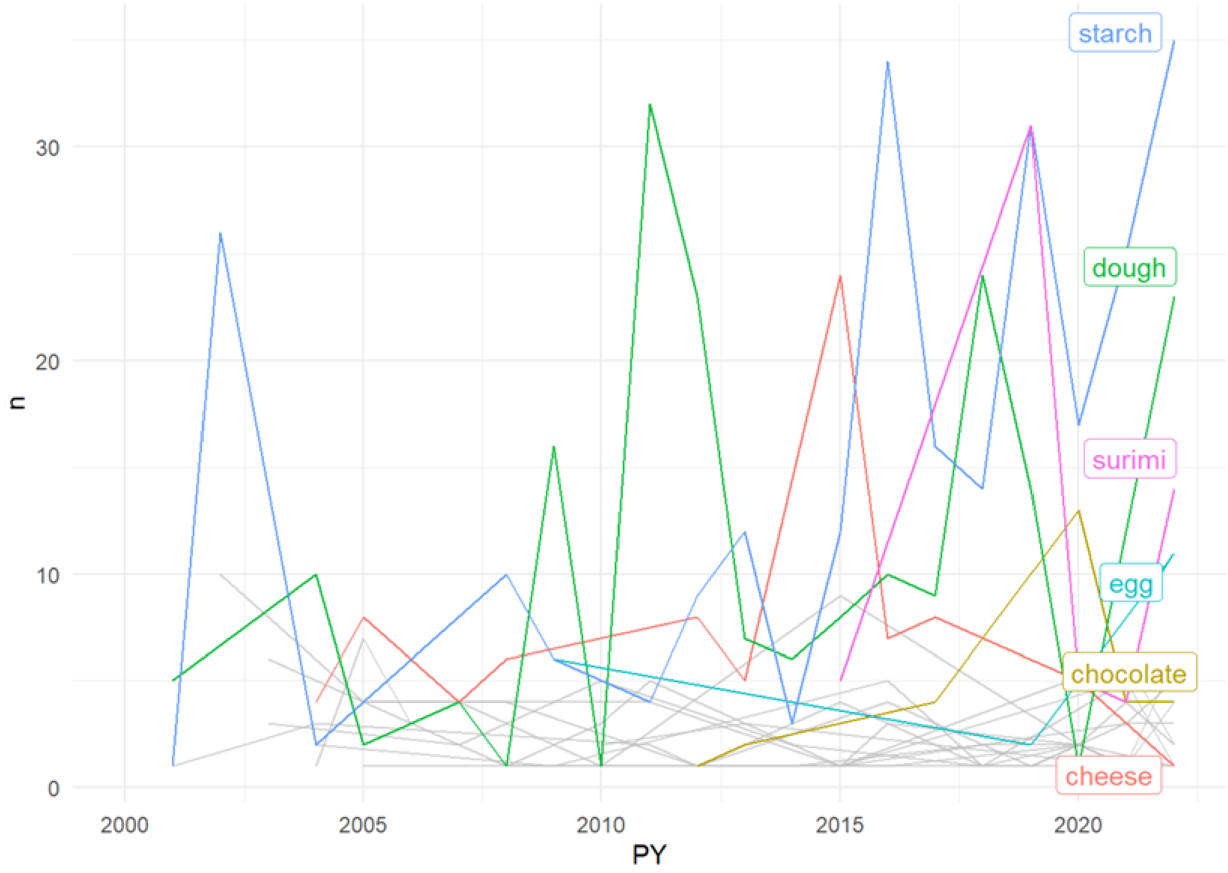

Figure 15: Evolution of publications on specific food types in 3DFP over the past two decades, using less stringent search criteria

The limited number of currently well printable food types corresponds with the capabilities of available food printers on the market (see section 5.2 on food printers).

5.1.2 Trends in the patent space

In order to gain insights into technology trends and innovations in 3DFP that may have been considered of commercial value, patent queries were conducted for the past 10 years in global patent databases from main IP Offices worldwide, namely: WIPO (patentscope), the World Intellectual Property Database; EPO (Espacenet), the European Patent Office, and USPTO, the US full text patent database. 2057 patent documents were obtained. From this original dataset China was found to dominate (1481 patents documents), however experts on Chinese patents estimate that possibly only 10% of filed patents are of value, due to low grant rates, and low commercialisation rates as well as industrialisation and commercialisation rates and a high proportion of abandoned patents (A. He & Centre for International Governance Innovation, 2021). Hence, in most of our analyses China is not included. For a deeper analysis of patents it was decided to focus on patent documents covering US, WO, EU, KR, JP and to focus on patent applications (rather than granted patents) in order to ensure the most recent “up and coming” technologies and applicants would be included as well as to avoid duplication of documents. 303 patent documents were finally analysed after narrowing down searches by direct relevance for 3DFP through critical researcher evaluation. Of those, 173 were directly related to 3D printing of food, which was the dataset finally analysed.

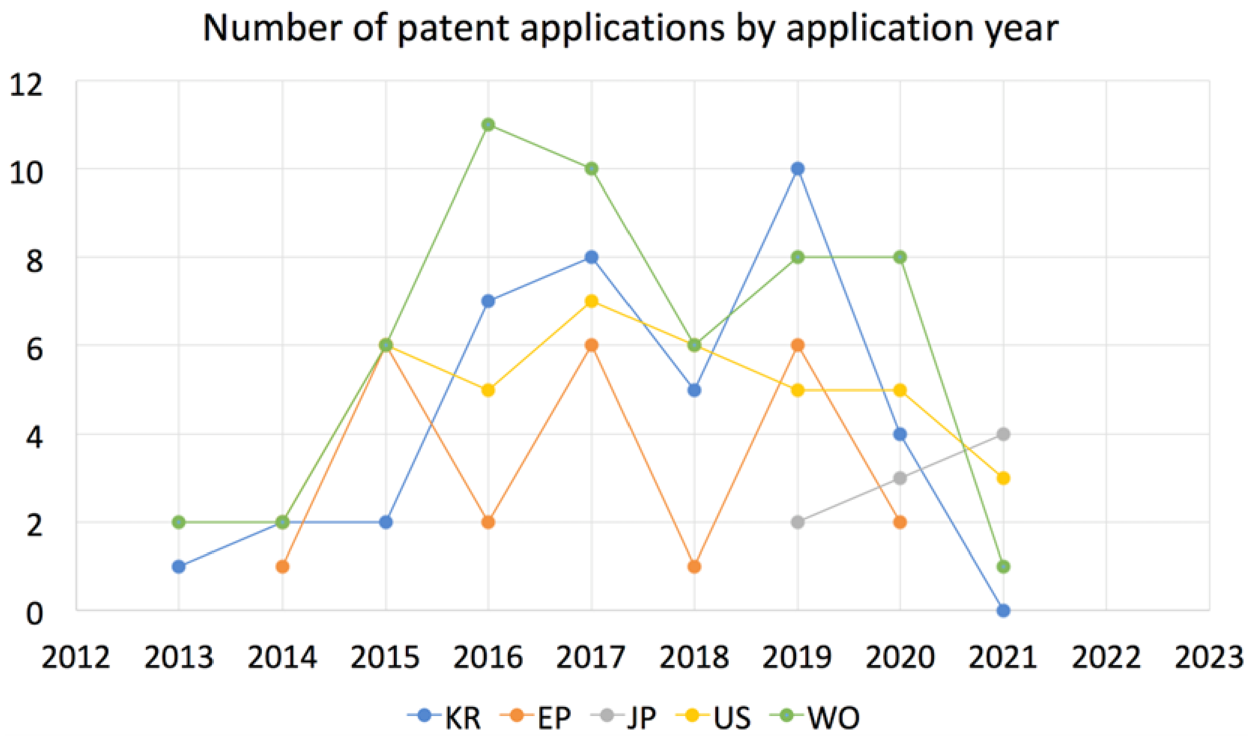

Figure 16: Number of patent applications in 3DFP over the past 10 years by geographical regions. Decline in applications in 2021 likely due to Covid-19 pandemic-related effects. (KR: Korea, EP: Europe, JP: Japan, US: USA, WO: Global).

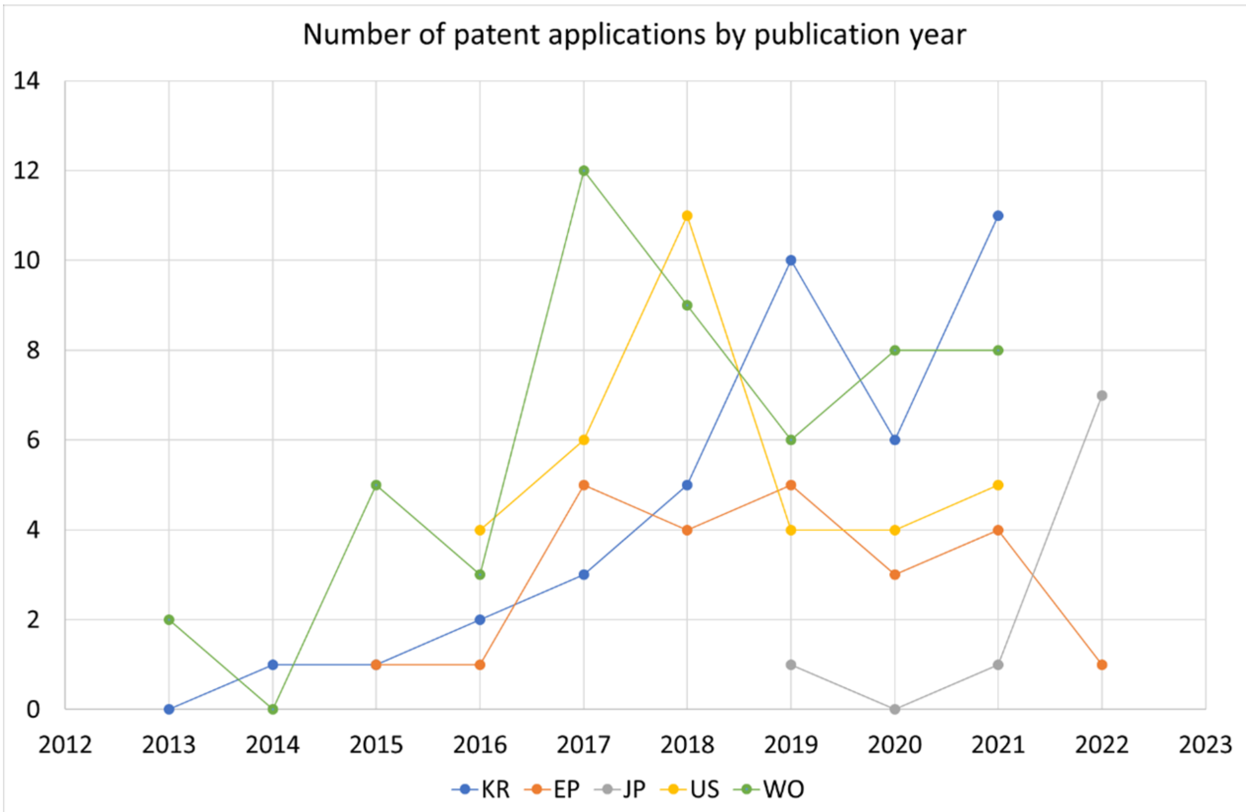

Figure 17: Number of patent applications for 3DFP by publication year and region (latest data included 30.11.2022)

Apart from confirming increasing peak activity in the past five years, generally low numbers of patents were filed, with possibly a drop in patent applications in 2020/21 due to the Covid-19 pandemic. However, one needs to consider that low patent numbers may not necessarily reflect only low interest in technology commercialisation, but might also indicate difficulties in finding prior art novelty in a crowded space of food production technologies based on similar technical principles. An analysis of most active assignees shows that a number of large companies in the food sector, as well as smaller startups, are patenting on 3DFP. However, few assignees hold more than one patent, including large Chinese and European research institutions such as TNO, in the Netherlands, large global corporations in the home appliances manufacturing sector such as, BSH (Bosch Siemens Hausgeräte GmbH), and in the food processing sector, such as General Mills (US), as well as small food 3D printer manufacturers, such as print2taste GmbH (Germany).

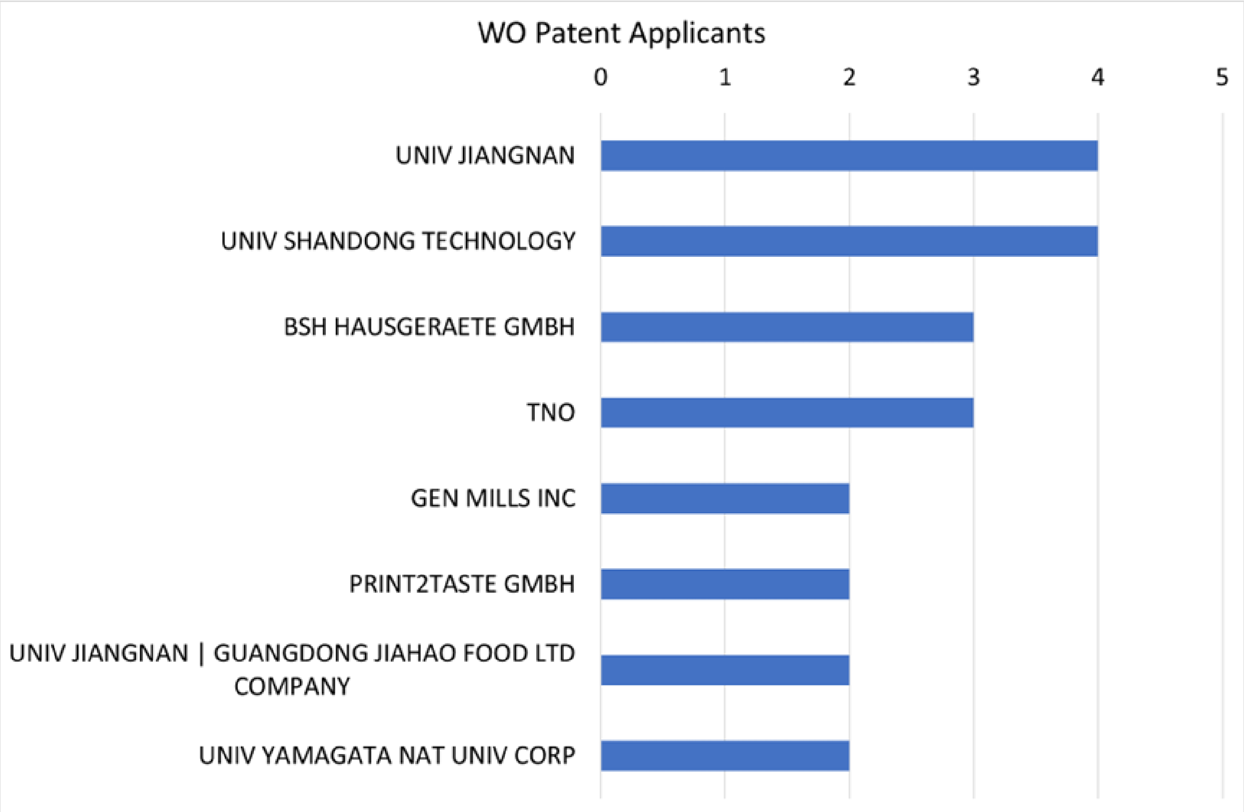

Figure 18: Most significant global patent applicants (WO) for 3DFP applications over the past 10 years.

Technology areas patented by the most significant applicants in 3DFP are shown in table 3 below.

Table 3: Technology areas covered by most significant global applicants

Applicant	Number of patents	Country	Titles

UNIV JIANGNAN	4	China	Microwave-coordinated three-dimensional printing apparatus, and accurate and efficient printing method for plant gel system Single nozzle 3d printing method for non-homogeneous recombinant food containing crushed rose flowers Three-dimensional printing method for food using microwaves and printer 3d accurate printing method for easy-to-swallow dual-colour mashed potato / mashed purple sweet potato cold dish
UNIV SHANDONG TECHNOLOGY	4	China	Method for use in preparing potato starch-based 3D printing material Composite starch 3D printing material preparation and process 3D printing method for ready-to-eat food 3D printing method for ready-to-eat food
BSH HAUSGERAETE GMBH	3	Germany	Control unit, food printer, and method for controlling a food printer Device, domestic appliance comprising such a device, method for producing a printing mass for a food printer, and system for producing a food Food-product printer with nozzle and printing plate

TNO	3	NL	3D printer system and method for filling a cartridge of such a system Method for the production of an edible object using SLS Method for the production of edible objects using SLS and food products
GEN MILLS INC	2	USA	3D printed foods shapeable food seasoning
PRINT2TASTE GMBH*	2	Germany	Microstructured food item Food composition
UNIV JIANGNAN | GUANGDONG JIAHAO FOOD LTD COMPANY	2	China	Method for 3D printing dual-colour stuffed pastry by means of concentrated fruit pulps Method for improving 3D-printing effect by means of prognostic processing of concentrated fruit pulp
UNIV YAMAGATA NAT UNIV CORP	2	Japan	Method and apparatus for three-dimensionally shaping food by irradiating mixture of starch powder and water with laser light Foodstuff three-dimensionally fabricated by combining block-form foods, and method for producing said foodstuff

In summary, patent search confirmed that only a very limited number of food types are currently printable and the intention to print vegetables and fruits as well as more complex mixtures of ingredients are very recent trends, possibly at least five years away from successful commercialisation.

5.2 3D Food printers on the market

From an engineering and hardware manufacturing perspective, 3D food printers are in essence just an extension of earlier existing 3D printing principles using a digital CAD file to build structures in an additive manner. The key premise of 3D and 4D food printing is customisation of shape, colour, flavour, texture, and nutritional content to meet specific individual needs. Similar to 3D printing in other industries, food printers are often advertised as customisation tools for food businesses, such as caterers, facilitating new food product development with the implication that they may have the potential to impact food supply chains by enabling wider access to food customisation. It is important however to differentiate between 3D printing for individual food preparation and other robotic automation of food production processes. The latter is mainly concerned with reduction of labour requirements in large scale production while most players in 3D printing of food emphasise uniqueness of design options, creativity, and ingredient control at the centre of the process (Sun et al., 2015). This distinction has become important also more recently, as several plant based and cultured meat producers are claiming to use ‘3D printing’ for making their products (see also section 3.5.2), however, when analysed more closely these applications are often not 3D printers in the conventional sense, but multi-nozzle micro-extrusion systems that apply some of the 3D printing engineering principles as only one step of a multi-step production process that these companies treat as proprietary and confidential.

Currently 3DFP is carried out both on universal and/or self-developed platforms. Universal platforms are modified open-source commercial printing platforms that are adapted for food printing purposes. These printers are not specific to food applications but universal desktop fabricators that are either compatible with the use of food materials, or can be made food compatible with hardware extensions, examples being the Fab@Home system and MakerBot. Such systems are limited in their food printing capabilities and mainly serve limited R&D purposes.

In contrast, self-developed platforms are built with considerations for desired outcomes and optimised for specific ingredient types. To develop such platforms there is a need for continuous expert research and improvement both for hardware development (for example to increase throughput or print consistency) and the formulation of ingredient mixtures and printing materials to reach optimisation (Sun et al., 2015).

Reviewing the food 3D printers currently available on the market it becomes clear that the choice is limited and defined by optimised input ingredient materials. Historically, food 3D printing started with sugar and chocolate as creative enhancements for the confectionery and cake customisation market. To date these materials remain the most printed food materials as they lend themselves to requirements of the technology easily due to their physical and chemical characteristics. However, over the past five years there have been considerable efforts to advance the technology to enable printability at scale of other food materials, such as different dough and starch-based foods, alternative proteins from plant-based sources, vegetables, fruits and semi liquids such as tomato sauce.

Apart from some limited successes with commercialising sugar and chocolate-based concepts, and to some extent alternative proteins from plant-based sources, the majority of these engineering efforts are mostly still at the R&D stage and are not available as commercial products yet. Given the various uncertainties with regards to technology robustness as well as with market definition, availability of such products to wider consumer segments is possibly at least five years away.

5.2.1 Printers specifically manufactured for food printing (self-developed platforms)

For a complete list of 3D printers purposefully designed exclusively for food printing see appendix A, table 6. A number of different printers were identified that can be classed as self- developed platforms specifically designed for food. A large proportion of them (4 out of 13 existing printers) focus on sugar and chocolate as printing materials with the most advanced also able to print various pastes from dough, vegetable purees and meat pastes. Examples of food printers currently on the market are:

- Foodini, Spain, is possibly the most advanced printer on the market with the ability to use five different foodstuff cartridges for the printing process, enabling the creation of complex foods such as jellies, pizza and spaghetti and potentially even a complete hamburger. The printer is produced by Natural Machines, Spain. The printers are currently only for rent and are not sold.
- MyCusini, Germany, produced by Print4Taste (previously print2taste) is a home printer for printing chocolate using pre-prepared chocolate refill packs that are sold with the printer.
- ProCusini, Germany, also produced by Print4Taste, and sold only B2B as a printer for professionals.
- Choc-Mate, Germany: produced by chocolate3. Apart from the printer the company offers pre-tempered chocolate sticks to be used with the printer so users can avoid the necessary pre-tempering step prior to printing.
- FELIX food printers, The Netherlands: A choice between three different printers is offered, with machines containing two different print heads either working simultaneously to increase volume being printed, or models can be loaded with different pastes to combine foods with the capability of printing pastes, chocolate, purées and meat. They are designed and manufactured by Felix Printers, a Dutch manufacturer of industrial 3D printers for a range of materials.
- byFlow food printers, The Netherlands: manufactured by byFlow and developed in partnership with Eindhoven based VDL Groep, a large industrial manufacturing firm. The printers are aimed at professionals in the bakery industry and they work with refillable cartridges for any sort of paste-type food to create customized meals. They claim that their printers can use either fresh ingredients or ingredients that otherwise would have been thrown away.
- Wiiboox Sweetin, China: is a food specific printer produced by a universal 3D printer manufacturer in China and prints chocolate and other sugar and starch based pastes, such as potato and fruit jam, white bean, and cream candy.
- Choc Creator V2.0 Plus: 3D prints chocolate; is/was manufactured by Choc Edge, UK, , a manufacturer of a chocolate printer and provider of printing services that started as a spinout of University of Exeter in 2012. We could not access the website for the company listed on crunch base while there are a number of pages for the business on social media and videos on YouTube. On some e-commerce sites there are pictures of a 3D printer by Choc Edge for sale, however the company was dissolved in November 2021 according to Companies House register.

5.2.2 Printers based on a universal 3D printer platform

Another group of printers is based on the universal platform concept, namely using general 3D printers that can also print food materials with or without specific hardware extensions. Printers are listed in Appendix A, table 8, and examples are:

- Zmorph FAB, Poland: Zmorph is a manufacturer of standard desktop 3D printers and according to the Zmorph FAB printer manual published on their website the printer can print Nutella®, chocolate, cookie dough, and some pre-prepared food 3D printer filaments. However, everywhere else the company has stopped advertising their printers as suitable for food printing.

- Wasp2040, Italy: Wasp is focused on 3D printers for industrial use and on their website food is not mentioned, however, they have been participating in exhibitions with 3D printers that were demonstrating food printing capabilities with a focus on gluten free food preparations.

In addition to 3D printer manufacturers there are also companies that sell printer parts as adapters/hardware extensions for food printing to be used with universal printers. Examples are ChocoL3D Kit and LuckyBot – 3DFP extruder, an add-on developed by Wiibox for general Wiibox 3D printers and other compatible home 3D printers.

When summarising currently available printers on the market it becomes clear that there is only a very small number of food 3D printer manufacturers offering actual printers as shown in figure 19.

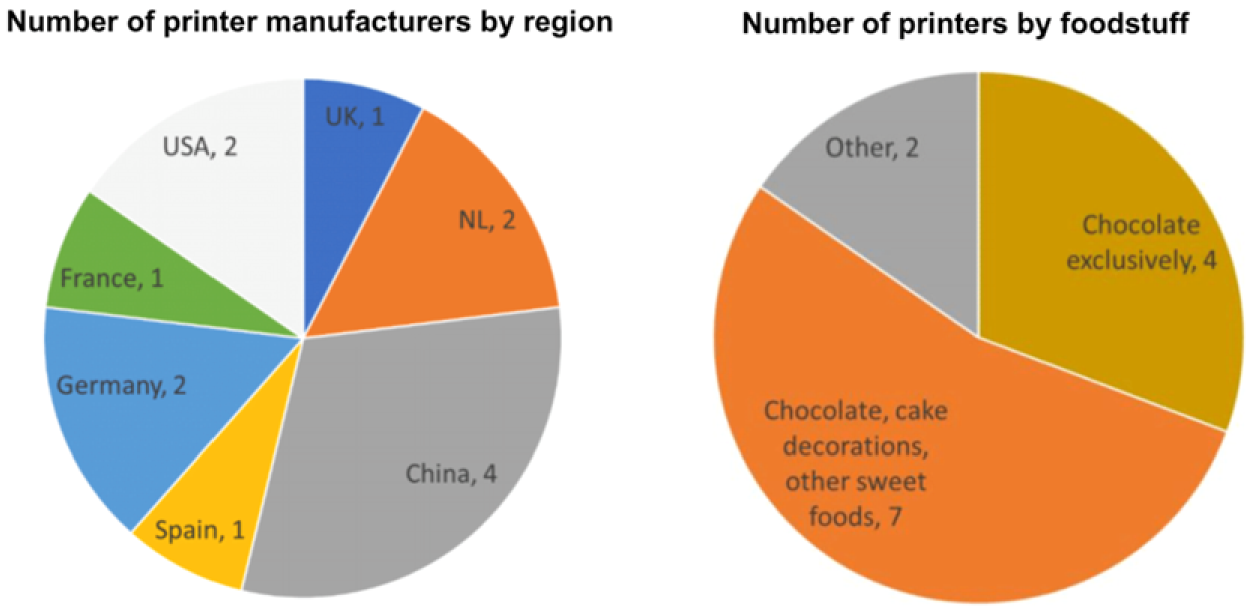

Figure 19: Number of printer manufacturers actually producing and selling food printers, by country (left), and number of printers by foodstuffs printed (right).

Looking into actual availability of printers, we also found a number of products that have been on the market earlier for some time but have recently stopped being traded, either because the company took the product from the market, or because the company ceased to operate, as indicated in figure 20 by *.

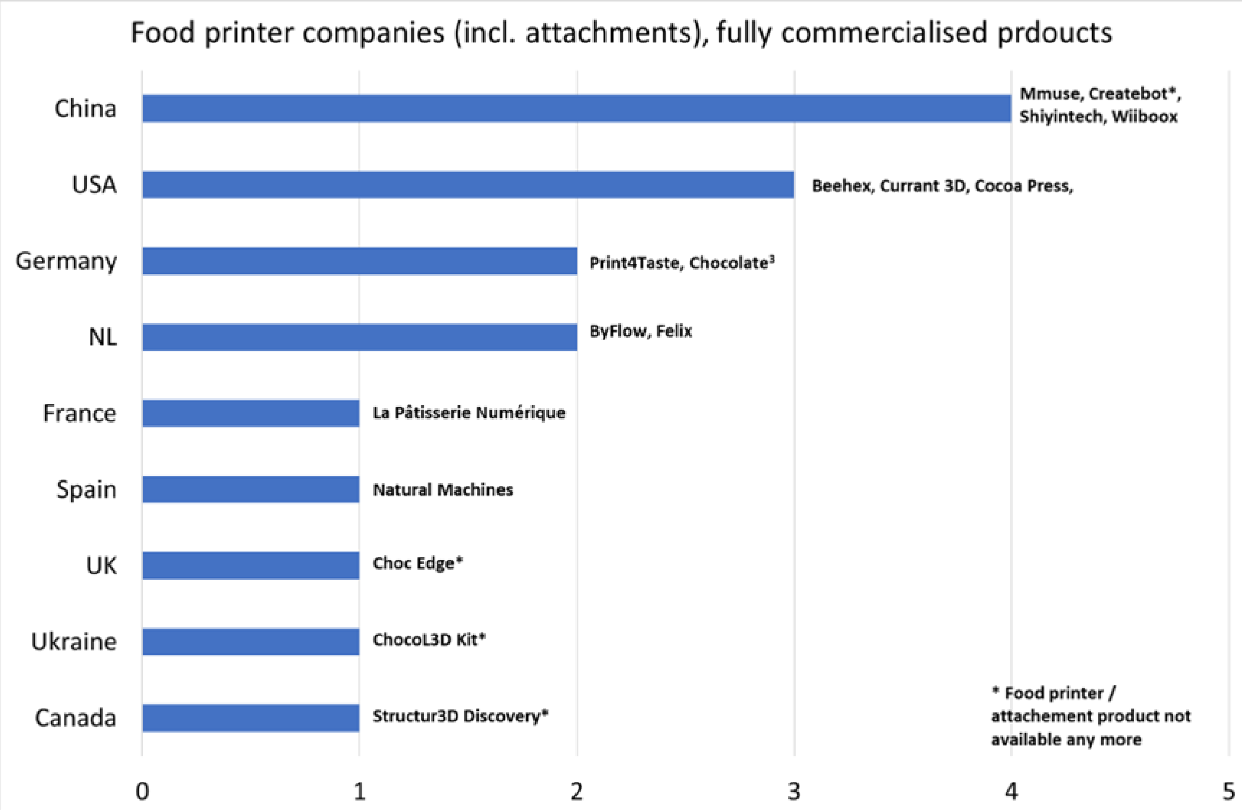

Figure 20: Currently available food printers and past products that are not any more traded, indicated by *

For a complete list of current and past printer manufacturers see also: Appendix A, tables 6, 7, 8. Some examples of printers offered in the past, or continuously postponed product launch are:

- Mmuse - New Desktop Chocolate 3D Printer, with no online evidence for active sales, but Youtube videos demonstrating the printing process. Possibly available on the Chinese market.
- Createbot - 3D food printer not available any more, produce other printers.
- Chefjet (may after almost 10 years in the making and internal business issues become available soon, but who knows?)
- CURRANT 3D Printer for sugar-based products, advertised, but not clear when finally on the market (earlier developed by Sugarlabs, US, almost 10 years ago).

A number of larger 3D printing companies have tried the food 3D printing market in the past, as evidenced by old web postings, and it seems they have meanwhile exited the market as no current food specific 3D printer could be found on their websites. This can be explained by the small market size, lack of viable business models and technical challenges that food 3D printing faces in adapting to higher throughput. Moreover, food printers need to be designed and optimised for specific food ingredients and truly 'universal' printers are unlikely to emerge in the near to medium future.

5.3 The 3D food printer/printing market

To put the small number of food 3D printers available on the market in perspective, it may help to look at the potential addressable market size for industrial 3D printing/additive manufacturing. As is common with such estimates, the figures can vary greatly, however two recent market studies estimate the general 3D printing market to be between \$8.6bn and \$12.9bn with a projected CAGR of 18.2-22.5% until 2026. In contrast the global market size for food 3D manufacturing was valued at $201m in 2022 and is estimated to reach $1.9bn by 2027 with a CAGR of 57.3%.

Clearly the market is small by dimensions, however there is an optimistic view of its growth rate. Nevertheless, it has to be taken into account that 3DFP faces the same challenges that industrial 3D printing has faced in the past, and to some extent does still face today, with the main challenge being the slow speed of production. In the manufacturing industry too there is a trade-off to be had between speed of manufacture and specialised features of the part that is printed, which means there has to be an economic advantage to higher customisation and/or complexity of the part compared to its cheaper mass-produced variants. In high value industries such as automotive, aerospace and medical devices this trade-off point has already proven to be economical for some applications. The main challenge in adapting the economics of 3D printing to the food industry is the commodity nature of food, being a low value, low profit, high volume business.

Reviewing concept startups, which alongside manufacture of self-developed 3D food printers aim to create concepts that have the potential to appeal to consumers, will shed more light on the specific challenges and opportunities the technology faces in establishing itself as a food manufacturing process.

5.4 The 3D food printing concept startup scene

Apart from self-developed 3D food printer manufacturers that are at the startup stage, there are also so called concept startups that innovate on enabling access, create printable foodstuffs and test business models for workability. Concept startups are listed in Appendix A, table 10. So far, commercial success has proven to be scarce, and the majority of these startups do not have an active product on the market but often advertise specific niche application areas, such as food for the elderly, children, or personalised nutrition applications. Examples of concept food printing companies using different foods are:

nufood started out in 2015 and currently offers “food flavour bursts”, small printed shapes of intensely tasting fruit juice-based objects that are used as sensory enhancers with food. It is described as the first food 3D printer that can print liquids that solidify after printing. The chemistry is based on combining fruit juice with powdered sodium alginate and dripping it into cold calcium chloride in a bowl. However, nufood is currently a brand held by Dovetailed, a design studio and innovation lab developing physical and digital experiences. The Nufood 3D printer is one item on its portfolio. The printer can be rented or rather the experience can be hired i.e. a demo of the printer can be bought for a number of guests and with up to three flavours. The products are small fruit flavoured cubes that can be enjoyed with other food or on their own. Dovetailed as a company has other lines of business that generate revenue.

Another 3DFP concept company that offers products on the market is the successor of Sugarlab in California, US. It was founded in 2011 with a focus on printing sugary decorative edible products for special occasions and was the original company developing the Chef Jet food printer. The founders are architects who started out by trying to print a birthday cake for fun. In 2013 3D Systems acquired Sugarlab. In a news piece from October 2022 the original founders bought back the technology from 3D Systems and were raising funds to develop a 3D printer (Chef Jet Pro) claiming that the printer can be developed to print a variety of foodstuffs.

A third example is the Dutch company Gastronology 3D Food Works, founded in 2019 and collaborating with the Dutch research organisation TNO, University of Eindhoven and Wageningen University. The company develops 3D food recipes and natural 3D food shapes for people with chewing and swallowing disorders, such as dysphagia, and it seems that it has reached a certain point of scale as it claims to be building a production line in the near future to print on an industrial scale for care homes and hospitals. The products are moist purées printed as solid, recognisable food shapes to enhance sensory experience for mostly elderly patients and with problems chewing and swallowing. Other advantages of food printing are described on their website as dosing of food portions, longer shelf life and use of residual products and food side streams.

Finally, food 3D printing technologies have been integrated by cultured meat or plant-based meat producers as one step in their production processes to improve textures. Some examples are:

- Revo Foods, Austria. The company focuses on producing plant based seafood alternatives and has been the winner of the EIT manufacturing BoostUp prize and has raised around €2m. Revo has also entered recently a collaboration with Swedish fungal protein producer Mycorena. However, industry insiders question whether their proprietary technology can be justifiably called 3D printing.
- RedefineMeat, Israel, produces plant-based meat. They have raised nearly $170m of funding between March 2019 and January 2022 to develop its 3D Alt-Meat Printer. The investment has helped to improve the palatability of their products for consumers and to increase scale of production. In October 2022 it entered a partnership with Giraudi Meats to enter the European market and use their distribution networks for its “New Meat” steaks produced on 3D printers.
- Steakholderfoods, Israel, produce cultured meat, (formerly MeaTech). The company has raised $17.9m in multiple fundraising rounds and went public in 2021. The company has entered a collaboration with Umami Foods, a Singapore based cultured seafood company, in 2022. Steakholderfoods currently does not have products on the market.

Figure 21: Examples of 3D printed food items as presented by their producers.

The above examples and other concept startups as shown in Appendix A, table 10, that have managed to commercialise products and/or services highlight the fact that the current state of 3DFP technologies, despite its advances in the past decade, limits products and services to niche markets. However, 3D printing technology may act as an enabling technology for other sectors, for example in the meat analogue market at the scale-up phase. Although RedefineMeat, Revo Foods, and Steakholder foods all plan to scale production or have done so, scaling 3D printing operations happens currently mainly through adding more printers to an assembly line of printers (printer farms). Given the added value 3D printing technologies may bring to the alternative meat sector, its products might become the first that bring 3D printing to consumers as a form of food processing technology that is not any more the main selling point for the final product. However, technology experts in 3DFP question whether these highly modified printing appliances can still be considered 3D printers.

5.5 Business models for 3D food printing

Food 3D printing is often advertised as a disruptive technology in the making, despite its current challenges with respect to technical performance and lack of commercial viability. Belief in its potential to ‘disrupt the food system’ is an established part of the academic discourse on 3DFP. However, with regards to viable business models it appears that the field is too immature to have any successful case studies to show, and conceptual discussions in the academic literature are mostly not based on empirical evidence. In addition, although specialist startups are working on optimisation of food 3D printers for niche applications, the “dominant design/s” for each of these has not yet emerged, which makes estimations of profitability difficult. In addition, most of the well understood challenges that currently exist for the technology still need addressing before economic modelling can become more evidence based and realistic. The root cause of the technical challenges is due to the fact that 3D printing is a technology invented and adapted initially to other industries and still to date many 3D food printers are adaptations of universal/general 3D printers to food materials. Although progress has been made in the past decade 3DFP faces still a number of key challenges to adoption and scale.

These challenges are around the following issues (Rogers & Streich, 2019):

- Consumer perception
- Manufacturing costs of printers and products
- Supply chain costs
- Change of manufacturing and supply chain models from centralised large scale to decentralised individual or batch production
- Complexity of 3DFP (not easily adaptable to non-specialist or domestic settings)
- Printed food consistency and quality
- Slow speed of printing process (not suitable for mass production)
- Lack of scalability (except if building printer farms)
- Lack of a large enough addressable market

These challenges have so far limited the technology to specific small niche applications. At the same time the advocates of the technology emphasise unique business model opportunities that the technology may have to transform the food industry, namely (Rogers & Streich, 2019):

- Product personalisation, customisation and differentiation
- Personalised nutrition (for people with health issues, athletes or health conscious individuals)
- Upcycling of food waste (food processing industry waste or retail waste)
- New textures and forms
- Creating palatability for new food sources such as algae, insects, and new plant varieties with unusual taste

Besides these considerations on ‘potential’ business models, based on discussions in the academic literature, our survey of 3DFP companies (see Appendix A, tables 6-10), allows grouping them by their service offerings in the following potential business model categories:

- Direct selling of printers (B2B and B2C)
- Selling of printed food products
- Selling of 3DFP services
- Selling of concepts, experiences/events and entertainment

5.5.1 Direct selling of Printers

Companies that manufacture and sell printers only, and do not work on concepts and products themselves are often manufacturers of general 3D printers which have extended their product line into food as well. Nearly all of them sell only to other businesses (B2B). Examples of 3D printer companies with successful demonstrations of 3D food printers are Felix, byFlow and 3D systems , which currently does not have a 3D food printer on the market yet.

We traced other large 3D printer manufacturers that either had produced a food 3D printer in the past, or experimented with development and sales of such, but since have withdrawn from the food 3D printing market. These include e.g. the Italian company WASP, which demonstrated a printer for printing gluten-free food, or the Polish company Zmorph, which has offered a food paste extruder for its standard 3D printers in the past, but do not sell it any longer. Currently Zmorph does not advertise food printing any more on its website.

Withdrawal from this market is not unexpected due to different factors such as small market size and the requirement for adapting 3D printer parts to the type of food it is printing. In addition, with the printer comes the need for the right consumables i.e. the formulation of specific foodstuffs to be printed, which can require considerable R&D efforts to optimise. At present, the only 3D food printer sold as a kitchen appliance for general consumers is the MyCusini home chocolate printer that comes with all accessories and pre-prepared chocolate filaments for use with the machine. This lack of home appliances is not surprising as the technology is still quite complex, needs to be adapted to each food type, and will require cartridges of the optimised food stuff to be delivered for printing, hence a significant B2C market for printers is unlikely to develop at this stage of technology readiness. What may evolve as a more realistic market is the B2B sales of printers to specialist food providers, as is happening to some extent with chocolate printers in the confectionery and catering sectors.

5.5.2 Selling printed food products

In this category successful companies develop their own 3D food printers adapting the printer to the intricacies of the food type they work with and sell the resulting product. This category can also be divided into two groups at this point in time. One group produces specific printed products that may eventually become mass-market products. Examples in this category are the above mentioned meat substitute producers, such as NovaMeat, Redefinemeat, which is one of the rare 3DFP companies with products on the market and expanding due to considerable investments raised, Steakholderfoods, and Revo Foods.

The second group develops and sells specialist niche products for a specific consumer group, for example companies such as BioZoon and Gastronology developing food for people with chewing and swallowing difficulties such as the elderly and dysphagia patients. Another example is Katjes, a confectionery company that has developed a 3D food printer specialising on printing fruit jellies. FabRX a UK printer manufacturer is developing 3D printing of solid pills and tablets, including nutraceuticals. Another UK company, Remedy Health with its brand "nourished", has developed a business printing personalised nutritional supplements in the form of jelly biscuits.

5.5.3 Selling of 3D food printing services

The most common service provided is still the printing of bespoke 3D food items, mainly as personalized and corporate gifts. Chocolate and sugar candy are still the dominating material for these items also in a B2B setting. Companies that offer professional services include large food manufactures such as Barilla (Italy) who provide a bespoke pasta printing service via its subsidiary Blue Rhapsody and training courses on how to use their printer. Also French company La Pâtisserie Numérique and Jan Smink, a Dutch restaurant owner offer training courses in food 3D printing, as well as Barry Callebaut, one of the largest cocoa processors globally, who operate "Mona Lisa, the first chocolate 3D printing studio". A few smaller companies offer services in bespoke printing, such as chocolate3, a company recently set up in Germany, which has also developed their own printer, or Chocolate Prints in Switzerland who also offer to operate "live" at various events and specialise in chocolate-based corporate themed advertising and give-aways.

5.5.4 Selling concepts, experiences/events and entertainment

In this category companies may or may not have their own specialist printer for sale, rather their focus is on generating and selling an experience. Here we have included the emerging limited number of restaurants that have 3D printed desserts and maybe some other printed food items on the menu. In this group the process of 3D printing and production of the end product is part of the experience package that is sold. Examples are nufoods/dovetailed, laMiam factory and smink, which is both a restaurant and a catering service. Other restaurants offering 3D printed food are La Boscana, which collaborates with FoodInk and La Enoteca, which uses Natural Machines' Foodini 3D food printers.

Other emerging integrated "experience" concepts are for example a printer developed by Beehex, called Cake Writer Pro™ for use inside bakery shops for customers to create and print their own designs, or the Japanese company "Open Meals" which is developing a business model of owning the whole value chain: from developing a printer, software and food powders to owning the restaurants for customers to consume 3D printed creations.

Some players in the 3DFP market hope to leverage synergies by partnering with larger established businesses. For example, byFlow, a Dutch manufacturer of food printers has partnered with Verstegen, a Dutch spice and sauce company, to deliver food printers together with the food inks adapted for the printer. They are currently also setting up a print farm for upscaling production of 3D printed products. This partnership aims to join the 3D printing expertise of byFlow with the capacity and long-term experience of Verstegen in food processing and preparation.

In summary, although occasionally the sellers of 3DFP experiences can get a lot of media attention, they operate mostly on small-scale events with low numbers of customers, or as part of a dining experience in a restaurant, hence will not reach wider consumer markets in the near future. In addition, they are mostly operating over limited periods of time to keep the experience interesting.

5.5.5 General considerations regarding business models

Literature research identified a very limited number of articles on business models in 3DFP. The publication of Rogers and Streich 2019 is seminal in the sense that they were the first to interview industry stakeholders explicitly on business models of 3DFP in depth, however, they could not identify any established or preferred business models in the industry and note that businesses turning a profit with printers are rare, and that 3DFP services are mainly sold to other businesses rather than directly to consumers (Rogers & Streich, 2019).

Jayaprakash and co-workers conducted an extensive interview and survey with industry stakeholders followed by a business modelling workshop developing business models for specific use cases such as customised design of chocolates, personalised snacks through vending machines and use of 3DFP in hospital kitchens (Jayaprakash et al., 2020). It is noteworthy that in the described value chain for all three examples there is a need for an ingredient manufacturer providing foodstuffs optimised for the printing process, emphasising the point that pre-preparation of food for 3D printing requires specific parameters that are not easily reproducible in non-specialist settings. Another commonality between the three explored value chains is that in each model there is a need for a printing operations provider; for chocolates in form of a design producer, for snacks an operator of 3DFP vending machines, and in the case of hospitals a specialist caterer. This means, end users are not operating printers in their own environment. In each case there is a specific interface for the end user/consumer to select options and place an order mainly through a web interface. Figure 22 shows a generalised value chain model for the three above mentioned business cases.

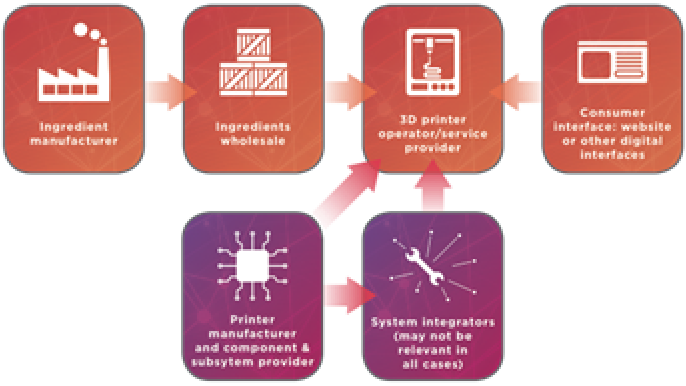

Figure 22: Generalised value chain model for three different 3DFP service offerings, showing the importance of a central service/printer operator. Modified from Jayaprakash et al., 2020.

It is not far-fetched to extrapolate that this generalised value chain model would be valid for a number of 3DFP service offerings, highlighting the fact that expert pre-preparation of ingredients is a bottle neck step in the supply chain. The authors also emphasise that developing business models for 3DFP is challenging as only real-world testing can prove their robustness.

One business case for 3DFP discussed since around 2012 is the potential to produce specialised food for the elderly and patients that have difficulties with chewing and swallowing. Nopparat and Motte describe the outcomes of a two-year project “Future Meals”, investigating the utility of 3DFP in food production for the elderly and patients suffering from dysphagia. In their model too, the value chain is similar to the one shown in figure 22, with separate operators for the preparation of food pastes and for printing the food (Nopparat & Motte, 2022).

An emerging business model for startups with a self-developed 3D food printer is in building collaborations with larger partners that can take on scaling, engineering and producing of the printers and food manufacturers that can bring expertise in preparation of food pastes at scale. We identified one example of such a model with three partners. byFlow a food printer developer, collaborates with VDL Group, a large industrial manufacturing firm and the food manufacturer Verstegen, all based in the Netherlands. This kind of three-way collaboration enables scaling of the operations with engineering skills of VDL group while byFlow and Verstegen focus on food pre-processing and printing.

Similar to any new technology, 3DFP exists in an ecosystem of players and its success depends on the robustness of the ecosystem and support levers for growth. Figure 23 shows the emerging ecosystem for the 3DFP industry.

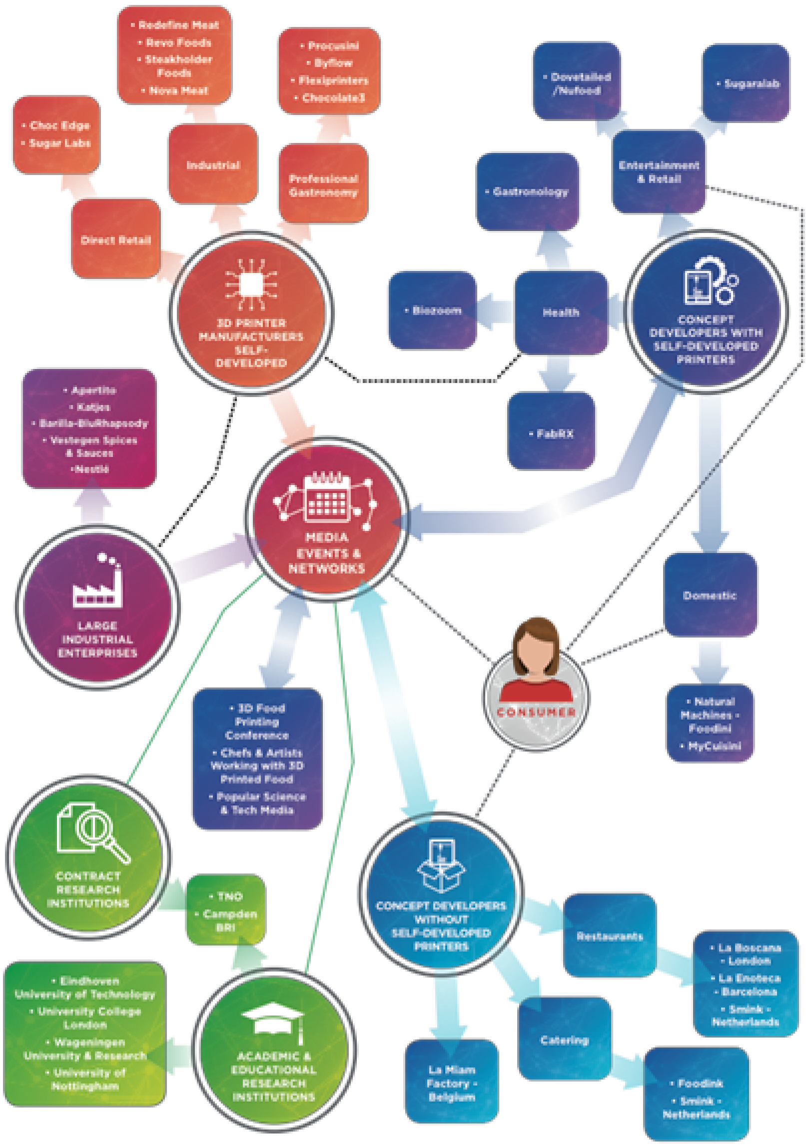

Figure 23: Ecosystem map of 3DFP operators and actors as mentioned in this report.

Media Events and Networks:

Concept Developers without self-developed printers

- Restaurants: la Boscana, London, La Enoteca Barcelona and Smink, Netherlands.
- Catering: FoodInk, Smink, Netherlands.
- La Miam Factory, Belgium.

?????Concept Developers with self-developed printers

- Entertainment and Retail: Sugarlab, Dovetailed/Nufood
- Health: Gastronology, FabRX, Biozoom
- Domestic: Natural Machines Foodini, MyCuisni

Contract research institutions

- TNO, Campden BRI

Academic and Educational Research institutions:

- Eindhoven University of Technology
- University College London
- Wageningen University and Research
- University of Nottingham

Large industrial enterprises

- Katjes
- Barilla-BluRhapsody
- Vestegan Spices and sauces
- Nestle

3D printer manufacturers self-developed

- Direct Retail: Choc Edge, Sugar Labs
- Industrial: Redefine met, Revo foods, Steakholder Foods, Nova Meat
- Professional Gastronomy: Procusini, Byflow, Flexiprinters, Chocolate3

Ecosystem integration faces currently some challenges with the main one being the absence of clear markets for products and services and the low performance of the technology. The latter refers to technical challenges such as:

- Need for adaptation of printers to food types and lack of a universal printer that can print any food
- Slow speed of printing/production
- Requirement for pre-preparation of food into printable pastes
- Complexity of technology for use by non-specialists
- Consumer perception, lack of information
- Being a technology driven market rather than a demand driven market

5.6 Sustainability claims around 3DFP

One of the claims made repeatedly in the academic and grey literature is the potential role of 3DFP in contributing to the sustainability of the food system. As these claims are made without any evidence based analysis or measurement framework to assess sustainability parameters of the technology, it would be wise for developers of business models to consider sustainability criteria for processes, products and supply chains from the outset. This in turn will directly impact the development of business models and help shaping the industry ecosystem. The main claims of the technology on impacting sustainability of the food system are (Rogers & Srivastava, 2021):

- Reducing waste by transforming food waste into edible food
- Recycling of surplus and close to expiry date food
- Shortening supply chains by printing food on demand locally
- Reducing the need for secondary packaging
- Creating palatable food from novel food sources such as algae, insects and unusual plant sources not known to the western consumer

Sustainability through food waste reduction

There are clear regional differences with the most food lost at the retail and consumer level in the USA and Europe, while due to lack of processing capabilities, the loss of food at production stage is highest in the rest of the world.

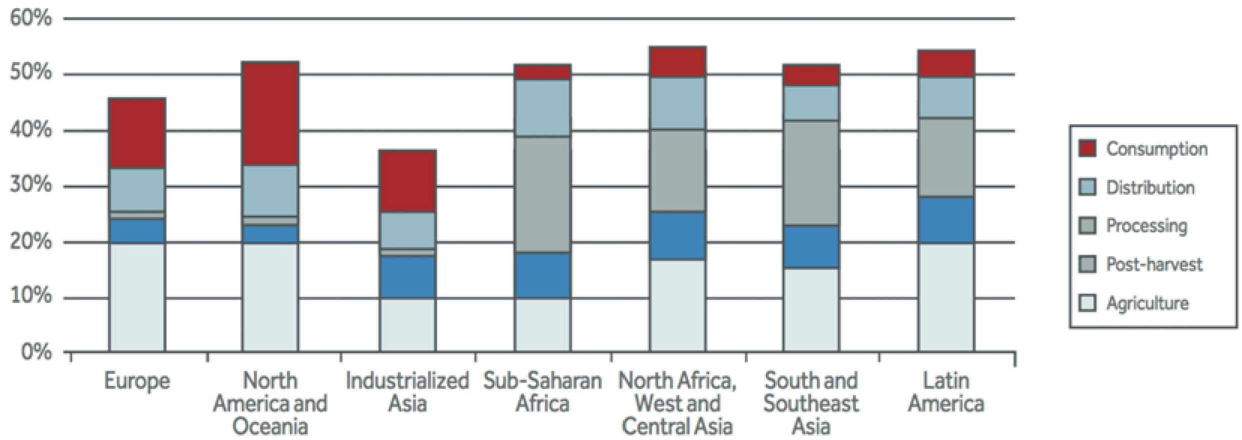

Figure 24: Levels of fruit and vegetable wasted along different stages of the supply chain in different regions of the world. Source Rezaei et al., 2017

Hence there might be a role for 3DFP in repurposing food waste if the technology could achieve a simplified, higher throughput capability, which then could be integrated in different parts of the food supply chain depending on regional requirements and be used to produce food that can be consumed as a main meal and not as the occasional food decoration or niche product. At present, the only startup focusing on this potential use of 3D printing is the Dutch company Upprinting Food, a spinout of Eindhoven University active since 2018, claiming to use retail fruit, vegetable and bread waste to formulate food inks transforming these waste streams into attractive products. It is unclear however, whether regulatory definitions of sell by dates and food expiry for human consumption would need to change in order to make such products commercially viable.

Sustainability through novel supply chain models

Rogers and Srivastava propose co-development of products and supply models with consumers to achieve the best outcomes for waste reduction (Rogers & Srivastava, 2021). They state that creation of an efficient digital services model for the user-centric value chains will improve access as well as customer and consumer attitudes and perception of 3D printed food. Elaborating on this central premise they suggest three potential different supply chain models for the 3DFP products namely the generative, facilitative and selective services at different price points. Figure 25 shows their schematic depiction of the models proposed.

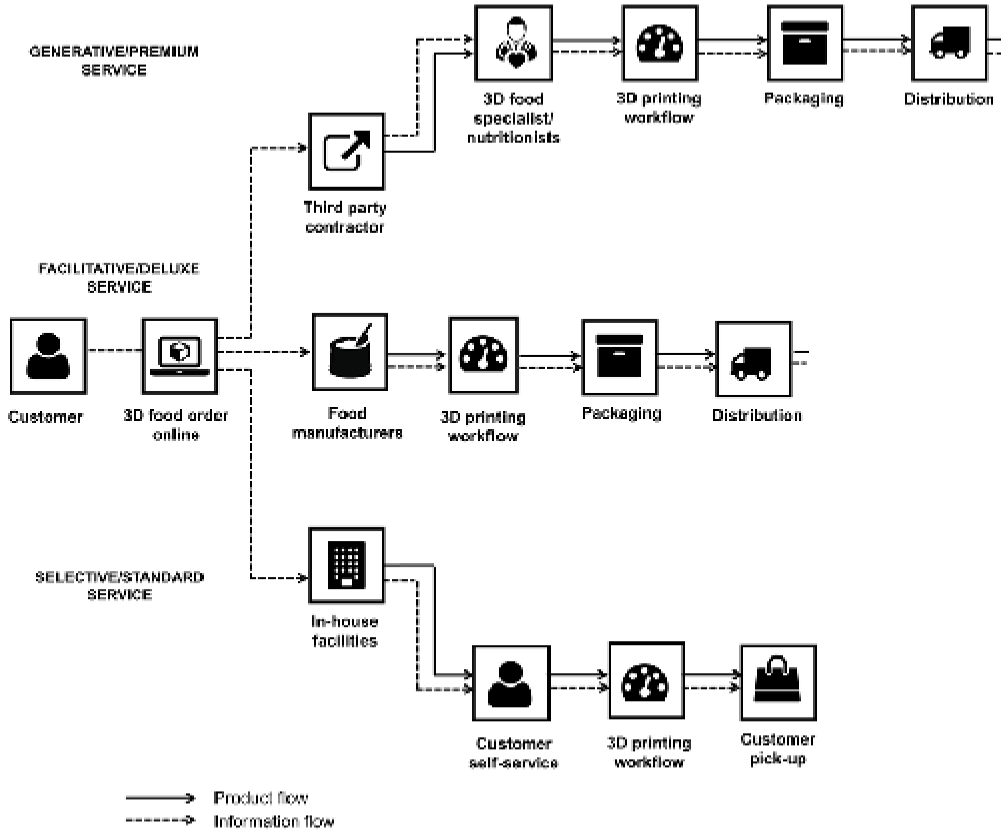

Figure 25: Three different proposed value chain models for 3DFP services at different price points. Source: Rogers & Srivastava, 2021.

All processes start with the customer and the 3D food order online.

Generate/Premium Service:

Third Party Contractor

- 3D food specialist/nutritionists
- 3D printing workflow
- Packaging
- Distribution

Facilitative/Deluxe Service:

Food Manufacturers

- 3D printing workflow
- Packaging
- Distribution

Selective/Standard Service:

- Customer self service
- 3D printing workflow

- Customer pick up

The Generative service model is a premium service operating as a one-stop shop for customers that are prepared to pay the required premium. The service is aimed at personalisation and individual requirement fulfilment. The Facilitative service model is about customisation not personalisation and is fulfilled by manufacturers that customise their products to groups of consumers rather than individuals. Finally, the selective service model is a standard service where the customer receives the instructions from the service provider and has to use potentially local 3DFP services to fulfil the production.

Similar to the value chain design work carried out by Jayaprakash et al. (Jayaprakash et al., 2020), what all three supply chain models have in common is the need for an actor that fulfils the optimisation of food ingredient formulations and printing operations while connecting to the customer via a digital interface. How from a supply chain model perspective a clear opportunity to increase sustainability of overall operations can be achieved, is currently not clear from these academic discussions.

Given the limitations of the technology at this stage to be scaled, except by creating printer farms, there is a clear need for further research into understanding its potential to contribute to the sustainability of the food system. So far, the potential supply models do not depart from the usual processing and logistics requirements of food production as it is today, with the need for equipment manufacturers, food processors, food printers and providers of logistics and delivery. Supply chain models for 3DFP already add one extra step to processing and that is the printing step itself. Therefore, there is a need for further evidence-based research to establish concrete sustainability criteria for the technology and its ensuing supply chain before plausible claims to radically impact the sustainability of the food system can be made.

5.7 Consumer trends and barriers

Since 3DFP has not made much progress with entering wider consumer markets since it first emerged as a tool to create unique designs for niche applications often in the confectionery sector, a number of players active in the field are now trying to position the technology as being able to deliver value around personalisation of food and nutrition. This appears to make sense at first, as 3D printing is known to deliver a high degree of customisation although at low throughput. It should be pointed out however that initially the strength of 3D printing was seen in its capability to create customised shapes, while applications in personalised foods or nutrition would need to focus on the technical capabilities in mixing ingredients in a highly controlled manner as well as creating personalised textures, which are application areas at an early stage of maturity at present. Irrespective of an indeed growing interest in personalisation options for food, 3D printed food is currently still unknown to most consumers (Brunner et al., 2018).

5.7.1 Consumer attitudes and acceptance of 3D food printing

A number of studies have recently tried to assess what the potential psychological barriers to consumer acceptance of 3DFP would be, by analysing attitudes and the willingness to try 3D printed food. Novel Food Technology Neophobia (NFTN) was found to be a significant barrier to acceptance of 3DFP, that could only be lowered to some degree by communicating very specific personal benefits and by an increased trust in science more generally (Ross et al., 2022). The same study also found that the expectation of ‘naturalness’ of food is one of the biggest barriers to the willingness to try 3D printed food. Consumer acceptance has also been studied with respect to whether labelling food as 3D printed would affect consumer perception (Feng et al., 2022). In this study that used conventionally produced chocolate swirls, gummy candy carrots and baked potato Smileys®, labelling these food items as 3D printed, but not more additional information on 3DFP, had a positive influence on the perception of the manufacture quality of the product, but not on taste or sensory ratings.

One of the very few studies testing 3D printed foods in a comparative manner was assessing consumer response and change of attitude to 3D printed snacks over a four-week period (Caulier et al., 2020). In this Dutch study participants overall liked the conventionally produced snack bar the best, confirming earlier results that consumers generally tend to rate foods as less satisfactory when they know that they were produced with novel methods (Novel Food Technology Neophobia). However, when they were repeatedly offered 3D printed bars with a range of customisation options with respect to textures and flavours, they rated the most ‘personalised’ bar the highest and their attitude towards 3D printed food changed after the experience. This finding correlates well with data from the largest interventional study on personalised nutrition, the food4me study, that could show that the perception of a high degree of ‘personalisation’ of dietary advice, irrespective of the scientific methods applied, had a positive impact on the motivation to follow the advice and achieve behavioural change around food intake or nutritional goals (Livingstone et al., 2021).

A comparative study has recently analysed the influence of contextual factors, such as location (at home, in a restaurant, festival, etc.) or social context (with friends, alone, with family etc.) on the willingness to try novel food experiences. The authors compared insect-based foods, cultured meat, plant based meat and 3D printed food, and found that overall willingness to try 3D printed food was similar to willingness to try cultured meat, while plant based meat was rated higher and insects lower. Social context did not have much of an influence, but 3D printed food was stated to be more likely to be tried in a restaurant or festival setting (Motoki et al., 2022).

In summary, consumers are initially sceptical of 3DFP in various study settings, and lack of the social aspects of food consumption, and lack of a ‘natural experience’ are main concerns. After being exposed to more information and potential settings in which 3D printed personalised food might become available, for example via vending machines or as snacks in gyms, consumers raised very practical concerns, such as the slow printing speed, or freshness of the product etc. (Jayaprakash et al., 2020).

5.7.2 Present ‘consumer interest’ in 3D food printing

Despite these limited insights into consumer attitudes that may offer a starting point to explore marketing strategies in the future, the main observation across studies is a lack of consumer knowledge about the technology. Given the possibility that 3DFP could find a foothold in a potential market of at home printing consumers selling printed foodstuffs locally or via social media, as has happened at a low scale with materials 3D printing as part of the maker movement, we wanted to assess whether traces of such activities can be found on social media. In order to gauge this kind of consumer interest in 3DFP more generally, we analysed openly accessible activity on social networks. Facebook/Meta, Twitter and Linkedin pages of 3D printer companies, as well as a number of online 3D printing groups on Facebook/Meta were analysed with regards to their numbers of followers and likes, as well as content on printing foodstuffs.

Table 4: Social media activity around 3D printing of food, and comparative other kitchen appliances.

Company	**Facebook followers**	**Linkedin Followers**	**Twitter Followers**
Choc Edge	1,600	81	1,087
chocolate^3	N/A	N/A	N/A
Felix printers	N/A	825	N/A
ByFLow (in partnership with manufacturer VDL Groep, Netherlands)	1,600	837	N/A
Shiyintech	N/A	32	13
Natural Machines	6,000	3,674	2,844
Print4Taste?GmbH, Germany	2,900	330	N/A
La Pâtisserie Numérique	248	1,017	N/A
Wiiboox	41,898	64	N/A
Mmuse	N/A	N/A	N/A

Company	Facebook followers	Linkedin Followers	Twitter Followers
Beehex	607	642	850
Createbot (note: foodprinter not available any more)	N/A	51 (China)	37
Culinary Printworks (also known as "Currant 3D & sugar lab")	9	445	N/A
Wasp (3D printer company)	15,506	8,288	4,295
Nutribullet (for comparison)	> 2 million		
Ninja kitchen (for comparison)	> 1 million		
Thermomix UK and Ireland (for comparison)	55,137		

Companies whose focus is 3D food printers generally have very few likes or followers on social media (from 10s to few 1000's). Companies whose general business is 3D printers for any kind of material have more likes (41k for Wiiboox and 15k for Wasp). When one compares the social media presence of these companies to other kitchen equipment, such as Nutribullet or Ninja Kitchen, one can safely say that there appears to be very little interest in 3DFP companies and products. Nutribullet reached 2 million followers on Facebook/Meta and Thermomix UK & Ireland alone has more than 55,000 followers.

When looking into Facebook/Meta discussion groups with a 3D printing focus and for the frequency of food printing related discussions looking for terms such as 'food' or 'chocolate', in general there were very few posts regarding the actual printing of food, and if food was mentioned it was general, for example with regards to the use of food safe materials for the 3D printing of items such as bespoke cookie cutters.

Table 5: Commentary on 3DFP in Facebook/Meta groups with a focus on 3D printing

Analysis of the following online groups	Members	Comments on food
3D Printing	195,000	Main discussion topic around food was the use of food contact materials, e.g. cookie cutters; Very little discussion on food itself – one re-posting of an introduction of chocolate print attachment by ChocoL3D Kit 3D printing for Beginners
3D printing for Beginners	17,000	No mention of food or chocolate found in any discussion
3D Printing UK	470	No mention of food or chocolate found in any discussion
3D Printing & Makers Things	4,900	Some posts from 2015 and 2016 on food. Richard Li (Foodbot logo) showed 3d printed roses; one post of chocolate printed luxury car logos by Wiiboox in 2021
3D Printing for Women and Girls	7,400	Discussion topic around food with regards to 3D printed food contact materials, but no content regarding the actual printing of foodstuffs

In summary, it appears that consumers are not ready and willing to embrace 3DFP at present and that consumer push is a highly unlikely driver of 3DFP in the near to medium future.

5.8 Potentially relevant regulatory implications for 3D food printing

Given that the field of 3DFP is still at an early stage of maturity there is currently no existing regulation directly targeting the technology and processes used. Literature on regulatory issues is also sparse, however academia and industry are aware of the role that regulation could play in the growth of the industry. We provide here a summary of the limited number of existing documents and legal arguments that relate to 3DFP.

One of the earliest publications on potential regulation of 3DFP considers 3DFP from the perspective of the US legal structure and highlights the challenges the legal system has to contend with should the technology become widely accessible, dividing them mainly into short and long term food safety issues (Tran, 2016). For the short term the author considers two potential scenarios, namely 3D printed food leading to food poisoning should it be mass marketed, or causing allergies in some individuals. These concerns are related to the relative unknown food safety aspects of operating 3D food printers with different foodstuffs over longer periods of time, and potential routes of contamination. Concerns about long-term issues are the currently unknown effects on human health after longer-term consumption of 3D printed foods, as these might be considered currently as 'highly processed' foods. Exploring this latter question from a health and legal perspective is currently as unresolvable as similar issues with other novel foods, because at present there is no evidence base to build legal arguments upon due to the lack of long-term population studies investigating the effects of 3D printed food on human health. Hence, the legal question of ultimate responsibility for 'health changes' as a result of long-term consumption of 3D printed foods is at present not addressable. Concerning labelling issues J.L. Tran finds similarities between 3DFP and GMO foods with the main issue being unknown long-term effects. Finally, the author quotes Candice Ciresi, Former General Counsel at Stratasys, who in 2016 at a keynote address at the University of Minnesota Law School has stated that "scientists are working on the possibility of creating food from chemical compounds, which could enable food printing to generate new food where scarcity exists".

Clearly using 'chemical compounds' to create food poses a novel challenge to human health as well as legal systems, which currently is not considered widely.

European authors who consider regulatory issues in their work on 3DFP focus particularly on the novelty aspect of 3D printed foods and food safety considerations. Regarding novelty they refer to the EU Novel Foods Regulation 2015/2283, update 2018, and pose the question whether new regulation is required specifically for 3D printed food, or whether the application of existing legal frameworks would be sufficient regarding food safety (Baiano, 2022; Portanguen et al., 2022; Rogers & Srivastava, 2021; The European Parliament and the Council of the European Union, 2015).

The European Novel Foods Regulation covers foods and food ingredients that have not been consumed by humans to a significant degree within the EU before 15th May, 1997. The regulation explicitly stipulates that this includes: "…foods resulting from production processes and practices, and state of the art technologies…, which were not used before 1997." Besides suggesting that 3D printed food might require some form of labelling in line with the Novel Foods Regulation, authors also consider labelling issues around the possibility that 3D printed food would use ingredients from waste streams such as expired foods or non-food grade chemical compounds to aid the printing process, or novel proteins such as insect proteins.

There have been some considerations as early as 2016 on the issue of 3DFP in Canada, stating that novel food applications should be required for foods that are produced using 3DFP technology. In addition, specific concerns were raised with regards to shelf life and printing additives. In Canada a novel food is defined as "a substance that does not have a history of safe use and has been manufactured, prepared, preserved, or packaged by a process that has not been previously applied to that food, and causes the food to undergo a major change; or genetically modified". The author also points out that under the Canadian Novel Foods Regulation long processing times of applications, between 6 months to two years needed to be considered if

3DFP businesses intended to apply.

It is important to note that despite the novelty and early stage of technology development, regulation could potentially help rather than hinder innovation. Early regulation by setting specific standards expected for safety, sustainability and human health will help researchers and the industry consider these norms early in the development and avoid costly revisions of technology to adapt to late coming regulation. Furthermore, timely regulation can help change consumer perspective of the technology as regulatory standards will help consumers calibrate their expectations and potentially build trust. As mentioned, discussion is required early whether there is a need for new regulation, or whether existing regulation would suffice with some modification.

One area that may prove relevant to take into consideration when looking at policy and regulatory design for 3DFP is the legislation governing 3D printing of medical devices and drugs. The USA Food and Drug Administration (FDA) has invested substantially in research to understand the field in relation to devices, drugs and the printers themselves for legislative purposes. FDA has already indicated that it may not consider 3D printing a traditional manufacturing process such as moulding and CNC milling and there is the possibility that 3D printers need to be considered as stand-alone medical devices. In depth research into 3D printing of medical devices and pharmaceuticals is out of the scope of this research, however it may be a relevant space to consider for further research to inform policy design.

Impact of 3D food printing on the UK food system

3DFP at its current state of the technology does not at present interact with the food system to any significant extent. As such, it has very limited opportunities to impact consumer health and safety, or other parts of the food system in the UK, mainly because there are not many food printers on the market globally, and sales appear to be in low numbers. However, this can rapidly change as young startups increasingly move towards optimising the technology for specific food types while a number of 3DFP concept startups are testing different business models that may attract consumer interest in the technology.

It is worth identifying the hubs and nodes in the emerging 3DFP ecosystem (see fig. 23) to establish bottlenecks in the system (such as for example preparation of food inks, or operation of printers) that may pose threats to consumer health as well as opportunities to work with the ecosystem and support it in building safety into the further evolution of the technology and process development. This is particularly important for consumer perception of an emerging 3DFP industry as it has its roots in the maker movement experimenting with a universal tool, the 3D printer, using sugar and chocolate for decorative food items which are not consumed in large quantities, hence not being perceived as a ‘serious’ food production technology.

However, as 3DFP moves now into working with a variety of food ingredients, such as vegetables, meat and fruits, which as whole foods are consumed in larger amounts, understanding food safety issues of 3DFP becomes a key issue. At present 3DFP is not regulated and food safety issues around the technology are not well understood at present, beyond common sense arguments, such as that printer parts need to be easy to inspect and clean and be cleaned regularly etc.

Another issue for consideration are the processes used for preparing food inks and the types, numbers and volumes of necessary additives that are used to make the food paste printable. There are currently no comprehensive studies on the nature of food pastes and the processes involved in preparing them and their short- and long-term impact on human health.

Likewise, post printing handling and processing of 3D printed food products itself may pose various risks and may need to be considered an integral part of the printing technology, requiring the setting of certain standards equivalent to other food processing technologies.

Finally, there is still the need for a better understanding and evidence based assessment of the claims made by developers of novel types of 3D printed foods around health as well as claims that the technology as such may contribute to the sustainability of the food system.

To that effect development of relevant safety, quality and sustainability criteria for food printers and processes would help all stakeholders in the 3DFP ecosystem to make most of future opportunities. Businesses would have a standard to work towards, and consumers a measure of what to demand from the products they will have the choice to purchase. This might also help build consumer trust and remove some of the currently existing negative perceptions around the technology.

Conclusions: 3D printing technologies in the food system for food production and packaging

In this section we present a summary of the main findings of this research, discuss implications for the FSA under consideration of its remit, and give general and specific recommendations that my inform future interactions of the FSA with an emerging 3DFP ecosystem.

7.1 Summary of main findings

Technology evolution

The technology initially started out over 15 years ago by explorative technologists, curious scientists and enthusiasts trying to use foodstuffs for printing on 3D printers that were developed for other materials. The early food ingredients used were chocolate and sugar pastes. Over the past decade, and in particular over the past 5 years a rapid increase in R&D efforts in research institutions as well as in a small number of startups and larger food processing and kitchen appliances companies has shifted the technology focus from decorative, “fun” and curiosity food items towards the printing of healthy foods, and foods for specific needs, such as for dysphagia patients. Diversification of printed food ingredients has also made clear that the optimisation and pre-processing of food inks are crucial steps for printing success, hence pre-processing needs to be considered an integral part of the technology. Also many novel printed food ingredients require post-processing, which in some instances also need to be considered an essential part of the printing process.

Besides a small number of startups that have driven the evolution of the technology, large food companies have shown a low level engagement with the technology for around a decade. For example Barilla, an Italian global leader in pasta production, has in collaboration with TNO, a Dutch research organisation, developed 3D pasta printing technology and has since offered 3D printed pasta through its subsidiary BluRhapsody. Another example of a large food manufacturing company collaborating with a 3DFP company startup is the collaboration between Verstegen, a Dutch sauce and soup manufacturer with byFlow, a Dutch food tech company with self-developed 3D food printers aiming to sell 3D food printers together with pre-prepared food paste cartridges.

Potential wider Impact of 3DFP

Despite some technological progress over the past decade, still only a small number of 3D printers have matured from the conceptual prototype stage to commercially available and viable products, most of them only in limited numbers in the context of semi-commercial startup settings. The most widely printed foods are still chocolate and sugar-based ingredients. Very recent developments enabling the printing of healthy ingredients, such as fruits and vegetables may enable a market for children or for food for the elderly and patients with difficulties swallowing. Other foods currently printable at small scale are cultured (in-vitro) and plant-based meat, pasta, dough-based baked foods and cheese. One of the key challenges of the technology is the need of adaptation and optimisation of printers to each food type as there is at present no universal 3D food printer that can print multiple food types at scale. Such multi-food printers, which are capable of printing more complex foods however, are at the prototype stage and may reach the market in the next five to ten years.

Wider systemic impacts of 3D printing of food are discussed in the academic literature and diversification of the technology through innovation into specific sub-niches indicate that 3D printing might act as an enabling or supporting technology for other technology-enabled trends in the food system, such as personalised nutrition, alternative proteins, use of food side- or waste streams, plant based meat alternatives, cultured meat, functional foods and health nutrition. Moreover, food printing currently appears to evolve from a focus on the shape aspect of printing towards finding solutions for real food processing challenges. This includes prototyping of novel foods to for example increase healthy ingredients such as fibre, or reduce salt, sugar and fat intake via printing of specific textures that modify the sensory experience of food. In the academic and grey literature claims are made about the future potential impacts of 3DFP around its ability to possibly increase sustainability of food production in some cases, or that it might enable business models of decentralised food production affecting supply chain models. Although such claims have been made repeatedly in the academic literature, supporting evidence is currently lacking due to the early stage of the technology and a lack of assessment frameworks.

3D printing for the production of food packaging

Information on the use of 3D printing technologies for the production of food packaging or food contact materials is at present scarce, but can be grouped into four categories:

- 3D printing used for prototyping in the food packaging industry:
- Large food packaging producers use 3D printing routinely for prototyping food packaging such as jars, containers, bottles etc, but use other mass production technologies to manufacture the final product.
- 3D printing used for the manufacturing of primary food packaging:
- Apart from small startups using 3D printers to test novel packaging concepts with novel (for example sustainable) materials, large packaging producers see 3D printing still as not suitable for the actual production of packaging due to its low performance and high costs compared to established manufacturing technologies.
- 3D printing as a proposed application for the production of “smart” packaging:
- Very limited academic research has tested possibilities to manufacture smart packaging elements with 3D printers. However, at current state of the technology it is unlikely that 3D printers can be used for mass production of such smart/intelligent packaging elements in the near to medium term future.
- 3D printed objects as food contact materials in applications other than packaging:
- Several examples of 3D printed food contact tools used sometimes at industrial scale have been identified, however none of these were of importance for packaging applications.

In summary, 3D printing technologies are not expected to contribute significantly to the production of food packaging in the mid to long-term future.

R&D developments in 3D food printing

R&D activities have been continuously increasing in the past decade, although from a very low base, with a sharp increase over the past five years and a number of R&D clusters are now well established, driving future developments of the technology. Research institutions outside of China with a strong focus in 3DFP are for example University of Queensland, Australia, McGill University, Canada, and Wageningen University, the Netherlands. Also Spain has not only two active universities carrying out research on 3DFP, but also a well-networked ecosystem of 3D printing technology developers in the Barcelona region leading to important synergies. Recent technology innovation is mainly focusing on making new and healthy food ingredients that have not been printed in the past printable and on improving robustness as well as throughput of the printing process. Progress in these areas may enable some applications to enter niche markets such as personalised foods, or foods for patients with swallowing difficulties at a larger scale.

Printers

Reviewing the food 3D printers currently available on the market it becomes clear that the choice is limited and defined by optimised print input materials. Historically, food 3D printing started with sugar and chocolate as creative enhancements for the confectionery and cake customisation market. To date these materials remain the most printed food materials, however, over the past five years there have been considerable efforts to advance the technology to enable printability at scale with other food materials, such as different dough and starch based foods, vegetables, alternative proteins from plant based sources, fruits and semi liquids such as tomato sauce. Apart from some limited successes with commercialising sugar and chocolate-based concepts, and to some extent alternative proteins from plant based sources the majority of these engineering efforts are mostly still at the R&D stage and are not available as commercial products.

3D food printing market

Looking at the numbers for the potential addressable market size for industrial 3D printing/additive manufacturing may explain the small numbers of printers on the market and the fact that a number of former food printer companies have failed after a few years trying to turn a profit. Current estimates of the 3DFP market are in the range of $201m in 2022, and is estimated to reach $1.9bn by 2027 with a CAGR of 57.3%. This compares to the wider 3D printing market at between $8.6bn and $12.9bn with a projected CAGR of 18.2-22.5% until 2026. Clearly the estimated market is at present small by dimensions, however there is an optimistic view of its growth rate, despite the well-known challenges the technology faces.

Startups

Besides a small number of 3D food printer manufacturers that sell their printers, there are a number of businesses that use 3DFP to sell specific experiences or personalised food items. These so called concept startups are
currently exploring different business models and products to find an entry point for the technology into wider consumer markets. 3DFP concept startups can be divided into two groups by the type of printer they use or sell, namely either their own self-developed 3D food printers, or universal printers adapted for food printing. Irrespective of printer type, concept startups sometimes offer food and dining experiences that include personalised food items as part of the experience, or showcases the actual printing process. Such companies often operate only temporarily at events or in collaboration with restaurants.

Business Models

Due to the nascent nature of the sector, there has not been much empirical research into real-world emerging business models as the current evidence base is slim, although some academic investigation of the issue has started over the past five years. Authors agree that the technology still faces a number of challenges to adoption and scale, despite the technological progress in the past decade. The challenges are mainly around the following issues:

- Consumer perception
- Manufacturing costs of printers and products
- Supply chain costs
- Change of manufacturing and supply chain models from centralised large scale to decentralised individual or batch production
- Complexity of 3DFP (not easily adaptable to non-specialist or domestic settings)
- Printed food consistency and quality
- Slow speed of printing process (not suitable for mass production)
- Lack of scalability (except if building printer farms)
- Lack of a large enough addressable market

As a result of these challenges the technology has been so far limited to specific niche applications. At the same time the advocates of the technology emphasise unique business model opportunities that the technology may have to transform the food industry, namely through enabling:

- Product personalisation, customisation and differentiation
- Personalised nutrition (for people with health issues, athletes or health conscious individuals)
- Upcycling of food waste (food processing industry waste or retail waste)
- New textures and forms
- Creating palatability for new food sources such as algae, insects, and new plant varieties with unusual taste

Besides these considerations on ‘potential’ business models based on discussions in the academic literature, our own survey of 3DFP companies (see Appendix A, tables 6, 7, 8), allows grouping them by their service offerings in the following potential business model categories:

- Direct selling of printers (B2B and B2C)
- Selling of printed food products
- Selling of 3DFP services
- Selling of concepts, experiences/events and entertainment

Like any new technology, 3DFP exists in an ecosystem of players and its success depends on the robustness of the ecosystem and support levers for growth. Expansion and further integration of this ecosystem currently faces key business challenges, namely the absence of clear markets for products and services besides the low performance of the technology, in particular the slow printing speed.

Sustainability

A potential for increasing the sustainability of the food system is one of the claims advocates of the technology make occasionally, which is also discussed in the academic and grey literature. However, evidence for these claims are scarce or non-existent and there is no evidence based analysis or measurement framework to assess sustainability parameters of the technology at this point in time. The potential sustainability impacts of the 3DFP technology are often stated as (Rogers & Srivastava, 2021):

- Reducing waste by transforming food waste into edible food
- Recycling of surplus and close to expiry date food
- Shortening supply chains by printing food on demand locally
- Reducing the need for secondary packaging
- Creating palatable food from novel food sources such as algae, insects and unusual plant sources not known to the western consumer

It has to be stated that a small number of academic authors point out the need for clear sustainability evaluation criteria as well as validation of the claims through relevant life cycle analysis for 3D printed foods from pre-printing processing of food pastes to post printing processes for making the product edible. Currently one Dutch startup, Upprinting Food, experiments with the up-cycling of retail bread and vegetable waste streams using 3DFP.

Consumer trends

Since its emergence as a tool to create unique designs for niche applications often in the confectionery sector, 3DFP has not made much progress with wider consumer adoption. Therefore, a number of players active in the field are aiming to position the technology around its ability to deliver personalisation for individual food and nutritional requirements. However, despite a general growing interest in personalisation options for food, 3D printed food is currently still unknown to most consumers.

Very limited consumer studies have also shown that Novel Food Technology Neophobia is a significant barrier to acceptance of 3DFP with the expectation of ‘naturalness’ of food being one of the biggest barriers to the willingness to try 3D printed food, which is perceived by many as not natural. Hence, consumer acceptance still remains a challenge for the sector and will require clear communication and trust building with consumers to advance wider acceptance of 3D printed foods. Furthermore, our own analysis of expression of consumer interest in 3DFP on social media has shown that there is no evidence that consumer push might be able to contribute to the evolution of the technology.

Regulation

Currently there is no regulation anywhere in the world that directly targets 3DFP technology and processes. Literature on potential regulatory issues is sparse. Nevertheless, both academia and industry are aware of the role that regulation could play for the growth of the industry. In discussions of European experts the focus is on the novelty aspect of the 3D printed foods and the related labelling and food safety considerations. Given that the EU has relevant legislation around novel foods, namely the EU Novel Foods Regulation 2015/2283 update 2018, the debate is mainly around whether this legislation suffices for regulating 3DFP products, or whether there is a need for specific regulation aimed at 3DFP. In the US academic literature on potential regulatory issues of 3DFP the focus is on food safety issues around the technology and the fact that there is no scientific evidence base to provide a baseline understanding of what required food safety parameters would be, should the technology reach maturity and reach wider consumer markets. Concerns have been raised also with regards to a lack of evidence for long-term health impacts of 3D printed foods, also due to the requirement of additives in many printed foods to aid the printing process. It is also acknowledged that early engagement of regulators could help set standards and in fact support the future evolution of the technology and build consumer trust.

7.2 Implications and recommendations for FSA

As the technology advances and potentially overcomes current barriers to scale it may enter larger markets with a variety of food items and its impact on the food system may grow. This means with regards to all main areas of concern for the FSA, namely food safety, authenticity, health and sustainability there will be a number of key aspects of 3DFP to consider when deciding on regulatory interventions.

3DFP is still at an early stage of maturity and will require time (5-10 years) to become more established as a food processing technology with a defined role in the food system both in B2B and B2C markets, with possibly B2B being commercially viable before B2C.

- The technology still faces a number of technical and societal challenges, mainly:
- Slow speed of production
- Upscaling the technology is challenging and in its current form only possible through 'printer farms'
- Requirement for expert pre-processing of foodstuffs into a printable food ink
- This step also entails the often essential addition of known food additives or novel substances to help viscosity and other parameters of the food paste to enable printability
- Consumer perception of 3DFP is at present not necessarily positive
- Consumers have a much more favourable view of 3D printing when it comes to printing chocolate and sugary decorative objects. However, skepticism is high when other food materials are to be printed with the intention to represent a main part of a meal
- 3DFP is often presented as best applicable to personalisation and customisation of food products and most new startups develop their products around narrow niche applications. Hence, there is at present no well-defined rapid growth market that would help the technology grow.
- Currently 3DFP technology is moving from the R&D and prototype stage to wider commercialization with the focus of technology development on making more food ingredients printable. Therefore the question of whether 3D printed food is safe to eat especially as a main meal in larger quantities and for long periods of time has not been considered yet in earnest or researched - and will be difficult to do before the technology has evolved further.
- Sustainability claims around the technology still require validation and will be strongly impacted by how supply chains and business models evolve.
- Food safety issues are likely to arise in two key parts of the 3DFP process, namely preparation of the food inks and the printing process itself, depending on printer type, temperature and time required for preparation and printing. In addition, optimisation of post-processing steps is important, as they can help address some of the food hygiene/safety issues.
- Business models and supply chains for 3DFP are not yet well defined and will impact the further development of the technology
- The key technical factor that will impact how business models will develop is the need for adapting food ingredients for printability in specific printers, which usually requires considerable prior R&D efforts or expert support.

Given that one promoted advantage of the technology is in enabling customisation and personalisation of products, it is highly likely that in such application areas production will be carried out in batch mode rather than in continuous process mode. This will pose its own challenges such as the requirement for full cleaning of printers after each batch as potentially ingredients and safety profiles between batches may vary, for example with respect to contaminating allergens or ingredient sensitivity to pathogens etc.

3DFP using food inks made from food waste/side streams or for repurposing food that is near its sell by date will require extra measures to ensure safety and authenticity of ingredients. Furthermore, the types and amounts of additives that are required to increase shelf life of pre-prepared food ink cartridges (which are now offered by some printer manufacturers together with printers) are currently not standardised and not tested for their health impact when consumed in larger quantities for longer periods of time.

Process hygiene for 3DFP is of a different scale compared to many other food processing methods, with multiple small and narrow parts in the printer including nozzles, tubing, mixing mechanisms etc., which are difficult to access or inspect on a routine basis, especially by non-experts. Given that currently the printing process is slow, the food material is exposed to ambient atmosphere and printer temperature for longer periods which itself may cause propagation of microorganisms. Furthermore, the porous nature of the printed food material may provide growth cavities for microorganisms. Hence the importance of optimisation and validation of the post-printing process steps to bake, freeze, fry or dry the products.

Advocates of the technology strongly emphasise the potential for the technology to have an impact on sustainability of the food system by bringing supply chains closer to consumers and reducing food miles, or its potential to repurpose food waste or near end of use food into new products. However, such claims are not proven and sustainability assessment criteria for measuring and comparing 3D printed food products with otherwise processed equivalents are currently lacking. It is likely that similar to other process technologies, energy, water and industrially produced additives will be used in considerable quantities and setting up 'printer farms' to scale the technology may in itself pose other sustainability challenges.

7.2.1 General recommendations for consideration

Given that commercial 3DFP is nascent and the ecosystem of commercial players has not matured sufficiently, it is difficult to immediately identify the hubs and nodes or entry points for leverage of regulatory action. In figure 23 we show an outline of the emerging ecosystem with current players mentioned in this report and the relationships they have built so far. Similar to any new emerging field, the media and how they report to the wider public plays a strong role in shaping the image and public opinion of the technology. 3D printed food is still seen as a futuristic curiosity rather than a serious food processing technology, hence consumer expectations may be shaped by this image of the technology. It can also be seen that although cautiously, large food manufacturers are entering the 3DFP ecosystem bringing considerable experience and commitment to food production safety standards to it. The 3D printer manufacturers are mainly concept developers creating bespoke printers for specific food types investing considerable R&D to make the printing process more robust. The consumer is currently more a spectator in this ecosystem rather than an active player, however this may change rapidly as soon as more printed food types find their way to market.

Considering this ecosystem structure, concept developers seem to be the current hubs of the nascent industry by bringing all other players together either in collaborations or through sales of printers and expert advice for setting up operations. Obviously not all concept developers have the same level of influence. This may change as the ecosystem evolves and some companies grow and take on multiple roles to cover the full value chain, namely from production of food inks to sales of final printed food products as has happened already in a very limited number of cases. Also, as larger food manufacturers enter the ecosystem and build their own supply and value chains around 3DFP the role of concept developers may change or fade. Nevertheless, at this point in time they are central influencing hubs that generate a lot of the media attention that the technology gets and are in the position to impact the growth and shaping of the industry.

In order to give an overview of the likely temporal evolution of the various elements of the 3DFP ecosystem see fig 26 below.

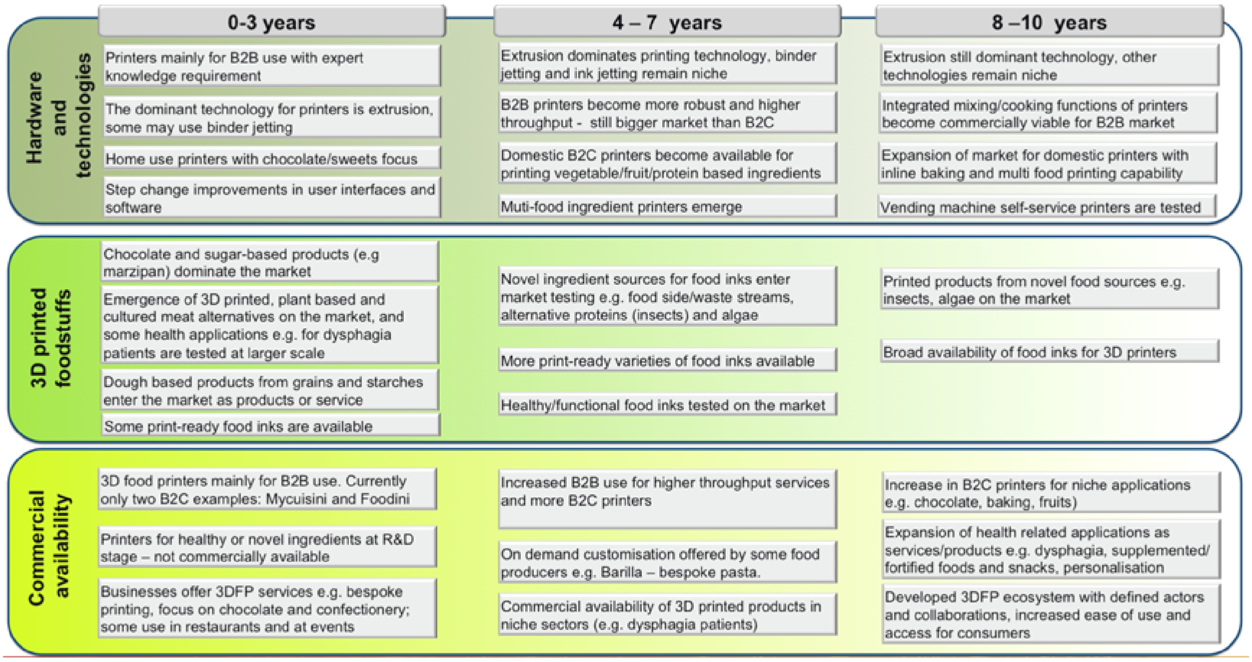

Figure 26: Indicative temporal evolution of hardware technology, formulation of foodstuffs, and commercial availability of 3DFP over the next 10 years.

In order to give a visual overview of different application areas/potential markets for 3DFP as they are indicated by current use of the technology and related R&D activities, see fig 27 below.

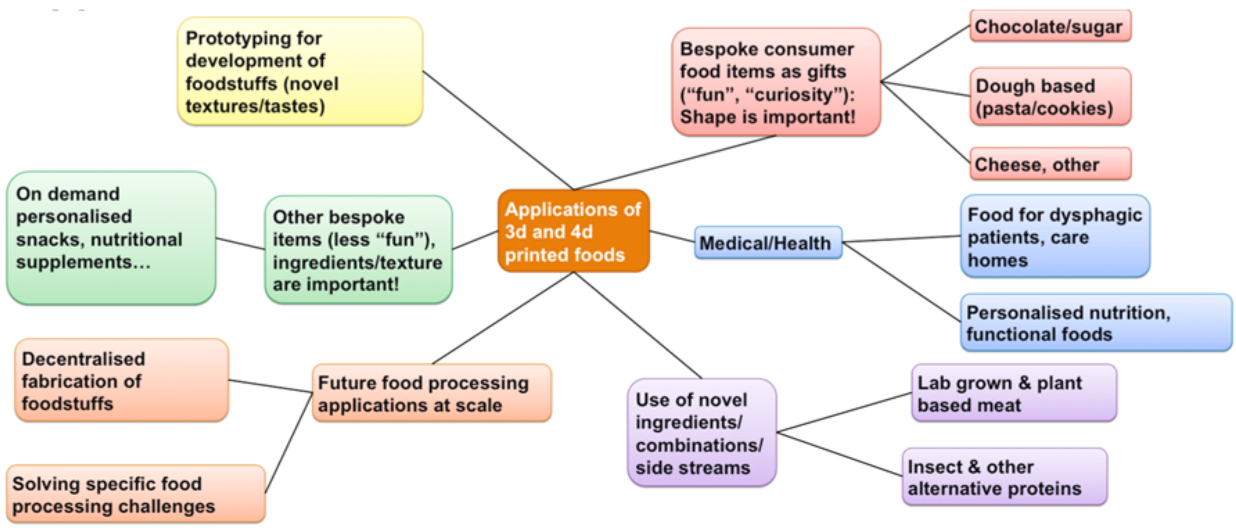

Figure 27: Overview of emerging application areas/potential markets for 3DFP.

Applications of 3D and 4D printed foods:

Prototyping for development of foodstuffs (novel textures/tastes)

Bespoke consumer food items as gift (‘fun’, ‘curiosity’ shape is important):

- Cheese, other
- Dough-based (pasta/cookies)
- Chocolate/sugar

Medical/Health

- Food for dysphagic patients, care homes
- Personalised nutrition, functional foods

Other bespoke items (less ‘fun’) ingredients/texture are important

- On demand personalised snacks, nutritional supplements

Future food processing applications at scale:

- Decentralised fabrication of foodstuffs
- Solving specific food processing challenges

Use of novel ingredients/combinations/side streams:

- Lab grown and plant based meat
- Insect and other alternative proteins

7.2.2 Short term FSA priorities (within 3 years)

Identify hubs and nodes and start engaging with the 3DFP ecosystem

- Concept developers are the hubs at the current stage of the ecosystem
- They would be key targets in the ecosystem to bring in manufacturing standards for their printers, food ink preparation processes as well as post processing steps
- Observe how the nature of the ecosystem changes as the technology develops further and the potential for scale emerges
- Set standards for labelling early in the technology evolution, as different printing technologies subject foodstuffs to different physical and chemical parameters as well as additives. This may impact the nature and nutritional properties of the end product.

Develop safety and hygiene standards for the emerging categories of printing processes:

- Printer farms
- Domestic printers
- On demand printers at local shops and supermarkets
- Small batch processors for highly personalised products
- Other emerging settings

Early prevention of potential food fraud

- Food inks for printing are complex and contain multiple ingredients which could be a target area for food fraud e.g. substituting ingredients with cheaper ones
- Decision on timing of regulation on labelling of products with regards to their novelty or degree of processing
- Early decisions of regulation and labelling may help with building consumer trust
- Engage with academia and research institutions
- Initiate more research on the impact of pre-processing, printing and post-processing on natural and nutritional properties of the food products
- Initiate research on health impacts of long term consumption of 3D printed foods as part of everyday nutrition
- Develop sustainability assessment criteria for 3DFP to enable validation of sustainability claims made by users of the technology.
- There is the potential of early regulation to help build consumer trust and support the industry in developing standards guiding developments in the manufacture of printers and development of printing processes.

7.2.3 Medium term FSA priorities (3-5 years)

- Continue research on the impact of pre-processing, printing and post-processing on natural and nutritional properties of 3D printed food
- Define standards for type and level of acceptable additives in the food ink preparations
- Establish consumer response to potential labelling requirements with regards to food ink ingredients and printing processes.

Consider assessment frameworks for the validity of claims made by 3DFP actors, and if necessary devise relevant regulation on the following claims:

- Nutritional quality
- Level of healthy/functional ingredients post processing for personalised/functional products
- Health claims and real impact on lives of specific groups such as elderly and patients with dysphagia
- Collaborate with relevant organisations, such as International Dysphagia Diet Standardization Initiative (IDDSI as they already have health impact frameworks of foods for their patient groups)
- Sustainability claims
- Water and energy use
- Real rate of conversion of food waste to real food
- Comparison with other processes with the same claim criteria in the production of healthy nutritious foods
- Continue engaging with the ecosystem players using hubs (emerging or current) as leverage points for health and safety controls.

7.2.4 Long-term FSA priorities (5 to 10+ years)

- Continue research on health impact of long-term consumption of 3D printed foods
- Establish standards of what printable foodstuff formulations (inks/pastes) are permitted. As the technical capabilities to make 3D printable food inks from many input materials will increase and it has already been speculated that there is the possibility to print "food" from chemical compounds originating from non-food material, it is important to establish definitions and inspection processes to clarify what can be printed and sold as food, and what not.

7.3 Limitations of study

We believe we have captured the most relevant areas of science and technology as well as commercial and societal trends immediately relevant to the current stage and future evolution of the 3DFP sector. 3DFP is a well-researched and studied subject with regards to technology developments, but little academic research is conducted on the commercial aspects of the field due to its early stage of market readiness. In our research we have captured the most relevant findings from the academic and grey literature available in the public domain. We have also expanded on the commercial information available by conducting a (to our knowledge) complete survey of food printers and companies, 3D food printer manufacturers, startups and larger food manufacturers entering the field. Lack of research on the commercial aspects of the sector is to some extent understandable, because despite a history of engineering research in 3DFP for over a decade, it is only recently that some viable commercial examples are emerging. The commercial and technical information provided in this report is from open sources. In-depth commercial and technical information about specific printers and products is often not available due to the short period of commercial activity of companies or is not made available to protect IP. Although we have taken care to report on most relevant trends impacting the 3DFP sector we have not attempted to quantify their impact in any form, as this would have required additional research and methods beyond the scope of this report. One major limitation for predictive analysis is the small size of the sector, and its early stage of maturity.

7.4 Proposed future research

There are a number of areas in which further in-depth research would help with expanding the evidence base for regulatory decision-making on 3DFP by:

- Gaining a better understanding of the pre-printing processes, additives used and storage and transportation requirements of food inks. These may be potentially different from other conventional food preparation processes because many food ingredients require specific proportions of additives and specific treatments to render them printable. However, these processes may change the ingredients and their nutritional profile considerably.
- Gaining a better understanding of the long-term impacts of consuming 3D printed foods on human health. This is particularly important for printed foods that are aimed at replacing main meals such as printed alternative meats or 3D printed food prepared for dysphagia patients and the elderly.
- Gaining a better understanding of the propensity of food to spoilage during the printing process. Given that the printing process is currently slow and is often carried out in ambient environments there is a possibility that food can become contaminated during the printing process. Also, the printed structures may have cavities and micro-structures that are not seen in natural food providing a suitable environment for microbial growth.
- Gaining a better understanding of the potential of the technology to impact sustainability of the food system. Currently advocates of the technology attribute sustainability benefits to 3DFP, however, these claims are not supported by evidence, and there is currently no measurement framework tested for suitability to assess 3DFP. Therefore, more in-depth research is required to better understand how the sector’s sustainability impact can be measured.

References: 3D printing technologies in the food system for food production and packaging

Agunbiade, A. O., Song, L., Agunbiade, O. J., Ofoedu, C. E., Chacha, J. S., Duguma, H. T., Hossaini, S. M., Rasaq, W. A., Shorstkii, I., Osuji, C. M., Owuamanam, C. I., Okpala, C. O. R., Korzeniowska, M., & Guine, R. P. F. (2022). Potentials of <scp>3D</scp> extrusion?based printing in resolving food processing challenges: A perspective review. Journal of Food Process Engineering, 45(4). https://doi.org/10.1111/jfpe.13996

ASTM International. (2022). ASTM ISO/ASTM52900-21 Additive manufacturing — General principles — Fundamentals and vocabulary.

Autonomous Manufacturing. (2020). How 3D Printing Transforms the Food and Beverage Industry.

Azzollini, D., Derossi, A., Fogliano, V., Lakemond, C. M. M., & Severini, C. (2018). Effects of formulation and process conditions on microstructure, texture and digestibility of extruded insect-riched snacks. Innovative Food Science & Emerging Technologies, 45, 344–353. https://doi.org/10.1016/j.ifset.2017.11.017

Baiano, A. (2022). 3D Printed Foods: A Comprehensive Review on Technologies, Nutritional Value, Safety, Consumer Attitude, Regulatory Framework, and Economic and Sustainability Issues. Food Reviews International, 38(5), 986–1016. https://doi.org/10.1080/87559129.2020.1762091

Bedoya, M. G., Montoya, D. R., Tabilo-Munizaga, G., Pérez-Won, M., & Lemus-Mondaca, R. (2022). Promising perspectives on novel protein food sources combining artificial intelligence and 3D food printing for food industry. Trends in Food Science & Technology, 128, 38–52. https://doi.org/10.1016/j.tifs.2022.05.013

Brunner, T. A., Delley, M., & Denkel, C. (2018). Consumers' attitudes and change of attitude toward 3D-printed food. Food Quality and Preference, 68, 389–396. https://doi.org/10.1016/j.foodqual.2017.12.010

Cao, Y., & Mezzenga, R. (2020). Design principles of food gels. Nature Food, 1(2), 106–118. https://doi.org/10.1038/s43016-019-0009-x

Caulier, S., Doets, E., & Noort, M. (2020). An exploratory consumer study of 3D printed food perception in a real-life military setting. Food Quality and Preference, 86, 104001. https://doi.org/10.1016/j.foodqual.2020.104001

Chen, C., Zhang, M., Guo, C., & Chen, H. (2021). 4D printing of lotus root powder gel: Color change induced by microwave. Innovative Food Science & Emerging Technologies, 68, 102605. https://doi.org/10.1016/j.ifset.2021.102605

Chow, C. Y., Thybo, C. D., Sager, V. F., Riantiningtyas, R. R., Bredie, W. L. P., & Ahrné, L. (2021). Printability, stability and sensory properties of protein-enriched 3D-printed lemon mousse for personalised in-between meals. Food Hydrocolloids, 120, 106943. https://doi.org/10.1016/j.foodhyd.2021.106943

Cotabarren, I. M., & Palla, C. A. (2022). Development of functional foods by using 3D printing technologies: application to oxidative stress and inflammation-related affections. In Current Advances for Development of Functional Foods Modulating Inflammation and Oxidative Stress (pp. 33–55). Elsevier. https://doi.org/10.1016/B978-0-12-823482-2.00009-1

Creativemachines Lab. (2022). Digital Food.

Derossi, A., Caporizzi, R., Paolillo, M., Oral, M. O., & Severini, C. (2021). Drawing the scientific landscape of 3D Food Printing. Maps and interpretation of the global information in the first 13 years of detailed experiments, from 2007 to 2020. Innovative Food Science & Emerging Technologies, 70, 102689. https://doi.org/10.1016/j.ifset.2021.102689

Dey, S., Hettiarachchy, N., Bisly, A. A., Luthra, K., Atungulu, G. G., Ubeyitogullari, A., & Mozzoni, L. A. (2022). Physical and textural properties of functional edible protein films from soybean using an innovative 3D printing technology. Journal of Food Science, 87(11), 4808–4819. https://doi.org/10.1111/1750-3841.16349

Diañez, I., Gallegos, C., Brito-de la Fuente, E., Martínez, I., Valencia, C., Sánchez, M. C., & Franco, J. M. (2021). Implementation of a novel continuous solid/liquid mixing accessory for 3D printing of dysphagia-oriented thickened fluids. Food Hydrocolloids, 120, 106900. https://doi.org/10.1016/j.foodhyd.2021.106900

Diañez, Isabel, Martínez, I., Franco, J. M., Brito-de la Fuente, E., & Gallegos, C. (2022). Advances in 3D printing of food and nutritional products (pp. 173–210). https://doi.org/10.1016/bs.afnr.2021.12.003

Dick, A., Bhandari, B., & Prakash, S. (2019). Post-processing feasibility of composite-layer 3D printed beef. Meat Science, 153, 9–18. https://doi.org/10.1016/j.meatsci.2019.02.024

Donn, P., Prieto, M. A., Mejuto, J. C., Cao, H., & Simal-Gandara, J. (2022). Functional foods based on the recovery of bioactive ingredients from food and algae by-products by emerging extraction technologies and 3D printing. Food Bioscience, 49, 101853. https://doi.org/10.1016/j.fbio.2022.101853

Enfield, R. E., Pandya, J. K., Lu, J., McClements, D. J., & Kinchla, A. J. (2022). The future of 3D food printing: Opportunities for space applications. Critical Reviews in Food Science and Nutrition, 1–14. https://doi.org/10.1080/10408398.2022.2077299

Everett, H. (2021). Columbia engineers cook 3D printed chicken with robotic lasers.

Fahmy, A. R., Amann, L. S., Dunkel, A., Frank, O., Dawid, C., Hofmann, T., Becker, T., & Jekle, M. (2021). Sensory design in food 3D printing – Structuring, texture modulation, taste localization, and thermal stabilization. Innovative Food Science & Emerging Technologies, 72, 102743. https://doi.org/10.1016/j.ifset.2021.102743

Feng, X., Khemacheevakul, K., De León Siller, S., Wolodko, J., & Wismer, W. (2022). Effect of Labelling and Information on Consumer Perception of Foods Presented as 3D Printed. Foods, 11(6), 809. https://doi.org/10.3390/foods11060809

Gebhardt, A., Kessler, J., & Thurn, L. (2018). 3D Printing: Understanding Additive Manufacturing. Hanser Publications.

Ghazal, A. F., Zhang, M., Bhandari, B., & Chen, H. (2021). Investigation on spontaneous 4D changes in color and flavor of healthy 3D printed food materials over time in response to external or internal pH stimulus. Food Research International, 142, 110215. https://doi.org/10.1016/j.foodres.2021.110215

Ghazal, A. F., Zhang, M., & Liu, Z. (2019). Spontaneous Color Change of 3D Printed Healthy Food Product over Time after Printing as a Novel Application for 4D Food Printing. Food and Bioprocess Technology, 12(10), 1627–1645. https://doi.org/10.1007/s11947-019-02327-6

Ghazal, A. F., Zhang, M., Mujumdar, A. S., & Ghamry, M. (2022). Progress in 4D/5D/6D printing of foods: applications and R&D opportunities. Critical Reviews in Food Science and Nutrition, 1–24. https://doi.org/10.1080/10408398.2022.2045896

Godoi, F., Bhandari, B., & Prakash, sangeeta. (2018). Fundamentals of 3D Food Printing and Applications (1st ed.).

Godoi, F. C., Bhandari, B. R., Prakash, S., & Zhang, M. (2019). An Introduction to the Principles of 3D Food Printing. In Fundamentals of 3D Food Printing and Applications (pp. 1–18). Elsevier. https://doi.org/10.1016/B978-0-12-814564-7.00001-8

Guo, C., Zhang, M., & Bhandari, B. (2019). Model Building and Slicing in Food 3D Printing Processes: A Review. Comprehensive Reviews in Food Science and Food Safety, 18(4), 1052–1069. https://doi.org/10.1111/1541-4337.12443

Guo, C., Zhang, M., & Devahastin, S. (2021). Color/aroma changes of 3D-Printed buckwheat dough with yellow flesh peach as triggered by microwave heating of gelatin-gum Arabic complex coacervates. Food Hydrocolloids, 112, 106358. https://doi.org/10.1016/j.foodhyd.2020.106358

Hao, L., Mellor, S., Seaman, O., Henderson, J., Sewell, N., & Sloan, M. (2010). Material characterisation and process development for chocolate additive layer manufacturing. Virtual and Physical Prototyping, 5(2), 57–64. https://doi.org/10.1080/17452751003753212

Haschick, J. (2018). 3-D Printing in the Food Packaging Industry. Food Technology Magazine.

He, A., & Centre for International Governance Innovation. (2021). What Do China's High Patent Numbers Really Mean?

He, C., Zhang, M., & Guo, C. (2020). 4D printing of mashed potato/purple sweet potato puree with spontaneous color change. Innovative Food Science & Emerging Technologies, 59, 102250. https://doi.org/10.1016/j.ifset.2019.102250

Jayaprakash, S., Paasi, J., Pennanen, K., Flores Ituarte, I., Lille, M., Partanen, J., & Sozer, N. (2020). Techno-Economic Prospects and Desirability of 3D Food Printing: Perspectives of Industrial Experts, Researchers and Consumers. Foods, 9(12), 1725. https://doi.org/10.3390/foods9121725

Johansson, M., Nilsson, K., Knab, F., & Langton, M. (2022). Faba Bean Fractions for 3D Printing of Protein-, Starch- and Fibre-Rich Foods. Processes, 10(3), 466. https://doi.org/10.3390/pr10030466

K. Handral, H., Hua Tay, S., Wan Chan, W., & Choudhury, D. (2022). 3D Printing of cultured meat products. Critical Reviews in Food Science and Nutrition, 62(1), 272–281. https://doi.org/10.1080/10408398.2020.1815172

Keating, K. (2018). 3D Printing and Food Packaging Design: What the Future Holds. WeListen

Khodeir, M., Rouaud, O., Ogé, A., Jury, V., Le-Bail, P., & Le-Bail, A. (2021). Study of continuous cake pre-baking in a rectangular channel using ohmic heating. Innovative Food Science & Emerging Technologies, 67, 102580. https://doi.org/10.1016/j.ifset.2020.102580

Kouzani, A. Z., Adams, S., J. Whyte, D., Oliver, R., Hemsley, B., Palmer, S., & Balandin, S. (2017). 3D Printing of Food for People with Swallowing Difficulties. KnE Engineering, 2(2), 23. https://doi.org/10.18502/keg.v2i2.591

León?Bravo, V., Moretto, A., Cagliano, R., & Caniato, F. (2019). Innovation for sustainable development in the food industry: Retro and forward?looking innovation approaches to improve quality and healthiness. Corporate Social Responsibility and Environmental Management, csr.1785. https://doi.org/10.1002/csr.1785

Li, S., Jiang, Y., Zhou, Y., Li, R., Jiang, Y., Alomgir Hossen, M., Dai, J., Qin, W., & Liu, Y. (2022). Facile fabrication of sandwich-like anthocyanin/chitosan/lemongrass essential oil films via 3D printing for intelligent evaluation of pork freshness. Food Chemistry, 370, 131082. https://doi.org/10.1016/j.foodchem.2021.131082

Lille, M., Kortekangas, A., Heiniö, R.-L., & Sozer, N. (2020). Structural and Textural Characteristics of 3D-Printed Protein- and Dietary Fibre-Rich Snacks Made of Milk Powder and Wholegrain Rye Flour. Foods, 9(11), 1527. https://doi.org/10.3390/foods9111527

Lille, M., Nurmela, A., Nordlund, E., Metsä-Kortelainen, S., & Sozer, N. (2018). Applicability of protein and fiber-rich food materials in extrusion-based 3D printing. Journal of Food Engineering, 220, 20–27. https://doi.org/10.1016/j.jfoodeng.2017.04.034

Lin, Y.-J., Punpongsanon, P., Wen, X., Iwai, D., Sato, K., Obrist, M., & Mueller, S. (2020). FoodFab: Creating Food Perception Illusions using Food 3D Printing. Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, 1–13. https://doi.org/10.1145/3313831.3376421

Lipton, J. I. (2017). Printable food: the technology and its application in human health. Current Opinion in Biotechnology, 44, 198–201. https://doi.org/10.1016/j.copbio.2016.11.015

Lipton, J. I., Cutler, M., Nigl, F., Cohen, D., & Lipson, H. (2015). Additive manufacturing for the food industry. Trends in Food Science & Technology, 43(1), 114–123. https://doi.org/10.1016/j.tifs.2015.02.004

Liu, Z., Bhandari, B., Guo, C., Zheng, W., Cao, S., Lu, H., Mo, H., & Li, H. (2021). 3D Printing of Shiitake Mushroom Incorporated with Gums as Dysphagia Diet. Foods, 10(9), 2189. https://doi.org/10.3390/foods10092189

Liu, Z., & Zhang, M. (2019). 3D Food Printing Technologies and Factors Affecting Printing Precision. In Fundamentals of 3D Food Printing and Applications (pp. 19–40). Elsevier. https://doi.org/10.1016/B978-0-12-814564-7.00002-X

Liu, Z., Zhang, M., Bhandari, B., & Wang, Y. (2017). 3D printing: Printing precision and application in food sector. Trends in Food Science & Technology, 69, 83–94. https://doi.org/10.1016/j.tifs.2017.08.018

Livingstone, K. M., Celis-Morales, C., Navas-Carretero, S., San-Cristobal, R., Forster, H., Woolhead, C., O'Donovan, C. B., Moschonis, G., Manios, Y., Traczyk, I., Gundersen, T. E., Drevon, C. A., Marsaux, C. F. M., Fallaize, R., Macready, A. L., Daniel, H., Saris, W. H. M., Lovegrove, J. A., Gibney, M., … Mathers, J. C. (2021). Personalised nutrition advice reduces intake of discretionary foods and beverages: findings from the Food4Me randomised controlled trial. International Journal of Behavioral Nutrition and Physical Activity, 18(1). https://doi.org/10.1186/s12966-021-01136-5

Lorenz, T., Iskandar, M. M., Baeghbali, V., Ngadi, M. O., & Kubow, S. (2022). 3D Food Printing Applications Related to Dysphagia: A Narrative Review. Foods, 11(12), 1789. https://doi.org/10.3390/foods11121789

Ma, Y., Potappel, J., Chauhan, A., Schutyser, M. A. I., Boom, R. M., & Zhang, L. (2023). Improving 3D food printing performance using computer vision and feedforward nozzle motion control. Journal of Food Engineering, 339, 111277. https://doi.org/10.1016/j.jfoodeng.2022.111277

Ma, Y., & Zhang, L. (2022). Formulated food inks for extrusion-based 3D printing of personalized foods: a mini review. Current Opinion in Food Science, 44, 100803. https://doi.org/10.1016/J.COFS.2021.12.012

Mantihal, S., Prakash, S., Godoi, F. C., & Bhandari, B. (2017). Optimization of chocolate 3D printing by correlating thermal and flow properties with 3D structure modeling. Innovative Food Science & Emerging Technologies, 44, 21–29. https://doi.org/10.1016/j.ifset.2017.09.012

Mikahila, L. (2022). How 3D-Printed Sustainable Packaging Meets Corporate Goals & Consumer Demands. 3D Natives

Molitch-Hou, M. (2021). BASF's Forward AM Certifies 3D Printing for Food Contact.

Motoki, K., Park, J., Spence, C., & Velasco, C. (2022). Contextual acceptance of novel and unfamiliar foods: Insects, cultured meat, plant-based meat alternatives, and 3D printed foods. Food Quality and Preference, 96, 104368. https://doi.org/10.1016/j.foodqual.2021.104368

Nachal, N., Moses, J. A., Karthik, P., & Anandharamakrishnan, C. (2019). Applications of 3D Printing in Food Processing. Food Engineering Reviews, 11(3), 123–141. https://doi.org/10.1007/s12393-019-09199-8

Navaf, M., Sunooj, K. V., Aaliya, B., Akhila, P. P., Sudheesh, C., Mir, S. A., & George, J. (2022). 4D printing: a new approach for food printing; effect of various stimuli on 4D printed food properties. A comprehensive review. Applied Food Research, 2(2), 100150. https://doi.org/10.1016/J.AFRES.2022.100150

New Food. (2022). 3-D printed cultured seafood agreement signed. New Food Magazine.

Nida, S., Moses, J. A., & Anandharamakrishnan, C. (2021). 3D printed food package casings from sugarcane bagasse: a waste valorization study. Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-021-01982-0

Nopparat, N., & Motte, D. (2022). The influence of business model on the development of 3D food printing technology for dysphagia patients in elderly care. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2022.09.028

Pant, A., Lee, A. Y., Karyappa, R., Lee, C. P., An, J., Hashimoto, M., Tan, U.-X., Wong, G., Chua, C. K., & Zhang, Y. (2021). 3D food printing of fresh vegetables using food hydrocolloids for dysphagic patients. Food Hydrocolloids, 114, 106546. https://doi.org/10.1016/j.foodhyd.2020.106546

Patra, S., & Young, V. (2016). A Review of 3D Printing Techniques and the Future in Biofabrication of Bioprinted Tissue. Cell Biochemistry and Biophysics, 74(2), 93–98. https://doi.org/10.1007/s12013-016-0730-0

Pérez, B., Nykvist, H., Brøgger, A. F., Larsen, M. B., & Falkeborg, M. F. (2019). Impact of macronutrients printability and 3D-printer parameters on 3D-food printing: A review. Food Chemistry, 287, 249–257. https://doi.org/10.1016/j.foodchem.2019.02.090

Portanguen, S., Tournayre, P., Sicard, J., Astruc, T., & Mirade, P.-S. (2022). 3D food printing: Genesis, trends and prospects. In Future Foods (pp. 627–644). Elsevier. https://doi.org/10.1016/B978-0-323-91001-9.00008-6

Pulatsu, E., Su, J. W., Lin, J., & Lin, M. (2022). Utilization of Ethyl Cellulose in the Osmotically-Driven and Anisotropically-Actuated 4D Printing Concept of Edible Food Composites. Carbohydrate Polymer Technologies and Applications, 3, 100183. https://doi.org/10.1016/J.CARPTA.2022.100183

Rogers, H., & Srivastava, M. (2021). Emerging Sustainable Supply Chain Models for 3D Food Printing. Sustainability, 13(21), 12085. https://doi.org/10.3390/su132112085

Rogers, H., & Streich, A. (2019, July). 3D food printing in Europe: Business model and supply chain aspects.

Ross, M. M., Collins, A. M., McCarthy, M. B., & Kelly, A. L. (2022). Overcoming barriers to consumer acceptance of 3D-printed foods in the food service sector. Food Quality and Preference, 100, 104615. https://doi.org/10.1016/j.foodqual.2022.104615

Shahrubudin, N., Lee, T. C., & Ramlan, R. (2019). An Overview on 3D Printing Technology: Technological, Materials, and Applications. Procedia Manufacturing, 35, 1286–1296. https://doi.org/10.1016/j.promfg.2019.06.089

Short, S., Strauss, B., & Lotfian, P. (2021). Emerging technologies that will impact on the UK Food System. https://doi.org/10.46756/sci.fsa.srf852

Sun, J., Zhou, W., Huang, D., Fuh, J. Y. H., & Hong, G. S. (2015). An Overview of 3D Printing Technologies for Food Fabrication. Food and Bioprocess Technology, 8(8), 1605–1615. https://doi.org/10.1007/s11947-015-1528-6

Tan, C., Toh, W. Y., Wong, G., & Lin, L. (2018). Extrusion-based 3D food printing – Materials and machines. International Journal of Bioprinting, 4(2). https://doi.org/10.18063/ijb.v4i2.143

Tay, Y. W. D., Panda, B., Paul, S. C., Noor Mohamed, N. A., Tan, M. J., & Leong, K. F. (2017). 3D printing trends in building and construction industry: a review. Virtual and Physical Prototyping, 12(3), 261–276. https://doi.org/10.1080/17452759.2017.1326724

The Commission of the European Communities. (2009). COMMISSION REGULATION (EC) No 450/2009 of 29 May 2009 on active and intelligent materials and articles intended to come into contact with food. Official Journal of the European Union.

The European Parliament and the Council of the European Union. (2015). REGULATION (EU) 2015/2283 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. Official Journal of the European Union L327/1.

Tomaševi?, I., Putnik, P., Valjak, F., Pavli?, B., Šoji?, B., Bebek Markovinovi?, A., & Bursa? Kova?evi?, D. (2021). 3D printing as novel tool for fruit-based functional food production. Current Opinion in Food Science, 41, 138–145. https://doi.org/10.1016/j.cofs.2021.03.015

Tracey, C. T., Predeina, A. L., Krivoshapkina, E. F., & Kumacheva, E. (2022). A 3D printing approach to intelligent food packaging. Trends in Food Science & Technology, 127, 87–98. https://doi.org/10.1016/J.TIFS.2022.05.003

Tran, J. L. (2016). 3D-Printed Food. Minnesota Journal of Law, Science & Technology, 17(2).

Vegconomist. (2022a). 3D-Printed Revo Salmon Now Available for Home Delivery in Austria.

Vegconomist. (2022b). Revo Foods: “In Five Years, Revo Will Be the Leading Provider of Plant-Based Seafood in the World.”

Verma, V. K., Kamble, S. S., Ganapathy, L., Belhadi, A., & Gupta, S. (2022). 3D Printing for sustainable food supply chains: modelling the implementation barriers. International Journal of Logistics Research and Applications, 1–27. https://doi.org/10.1080/13675567.2022.2037125

Waghmare, R., Suryawanshi, D., & Karadbhajne, S. (2022). Designing 3D printable food based on fruit and vegetable products—opportunities and challenges. Journal of Food Science and Technology. https://doi.org/10.1007/s13197-022-05386-4

Wainwright, O. (2013). 3D-print your face in chocolate for that special Valentine’s Day gift. The Guardian.

Wang, W., Yao, L., Zhang, T., Cheng, C.-Y., Levine, D., & Ishii, H. (2017). Transformative Appetite: Shape-Changing Food Transforms from 2D to 3D by Water Interaction through Cooking. Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, 6123–6132. https://doi.org/10.1145/3025453.3026019

Wegrzyn, T. F., Golding, M., & Archer, R. H. (2012). Food Layered Manufacture: A new process for constructing solid foods. Trends in Food Science & Technology, 27(2), 66–72. https://doi.org/10.1016/j.tifs.2012.04.006

Wilms, P., Daffner, K., Kern, C., Gras, S. L., Schutyser, M. A. I., & Kohlus, R. (2021). Formulation engineering of food systems for 3D-printing applications – A review. Food Research International, 148, 110585. https://doi.org/10.1016/j.foodres.2021.110585

Yan, Q., Dong, H., Su, J., Han, J., Song, B., Wei, Q., & Shi, Y. (2018). A Review of 3D Printing Technology for Medical Applications. Engineering, 4(5), 729–742. https://doi.org/10.1016/j.eng.2018.07.021

Yang, Q., Gao, B., & Xu, F. (2020). Recent Advances in 4D Bioprinting. Biotechnology Journal, 15(1), 1900086. https://doi.org/10.1002/biot.201900086

Zhai, X., Sun, Y., Cen, S., Wang, X., Zhang, J., Yang, Z., Li, Y., Wang, X., Zhou, C., Arslan, M., Li, Z., Shi, J., Huang, X., Zou, X., Gong, Y., Holmes, M., & Povey, M. (2022). Anthocyanins-encapsulated 3D-printable bigels: A colorimetric and leaching-resistant volatile amines sensor for intelligent food packaging. Food Hydrocolloids, 133, 107989. https://doi.org/10.1016/j.foodhyd.2022.107989

Zhang, Long?zhen, Dong, H., Yu, Y., Liu, L., & Zang, P. (2022). Application and challenges of <scp>3D</scp> food printing technology in manned spaceflight: a review. International Journal of Food Science & Technology, 57(8), 4906–4917. https://doi.org/10.1111/ijfs.15879

Zhang, Lu, Lou, Y., & Schutyser, M. A. I. (2018). 3D printing of cereal-based food structures containing probiotics. Food Structure, 18, 14–22. https://doi.org/10.1016/j.foostr.2018.10.002

Zhang, Z., Demir, K. G., & Gu, G. X. (2019). Developments in 4D-printing: a review on current smart materials, technologies, and applications. International Journal of Smart and Nano Materials, 10(3), 205–224. https://doi.org/10.1080/19475411.2019.1591541

Zhu, S., Ribberink, M., de Wit, M., Schutyser, M., & Stieger, M. (2020). Modifying sensory perception of chocolate coated rice waffles through bite-to-bite contrast: an application case study using 3D inkjet printing. Food & Function, 11(12), 10580–10587. https://doi.org/10.1039/D0FO01787F

Zhu, S., Vazquez Ramos, P., Heckert, O. R., Stieger, M., van der Goot, A. J., & Schutyser, M. (2022). Creating protein-rich snack foods using binder jet 3D printing. Journal of Food Engineering, 332, 111124. https://doi.org/10.1016/j.jfoodeng.2022.111124

Zoran, A., & Coelho, M. (2011). Cornucopia: The Concept of Digital Gastronomy. Leonardo, 44(5), 425–431. https://doi.org/10.1162/LEON_a_00243

Appendix A: Lists of 3D food printers and 3DFP companies

Table 6: List of 3D food printers purposefully developed for printing food materials

Most of these printers are commercialised, but their level of commercial success differs and is unpredictable at present as the market is just emerging. Note: 2D printers, such as PanCakebot or Pancake printer by Zbot are not included in this list.

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Company name and printer models	Food types	Capability/ USP	Commercial status

Choc Edge (UK) Choc Creator V2 Plus (earlier models)	Chocolate	Syringe loading system: users must manually insert tempered and heated chocolate into the 3D printer’s 30-mL syringe. Company also offers bespoke printing services.	Dissolved in Nov 2021 (Was fully commercialised)
chocolate³ (Germany) Choc-Mate	Chocolate	Advanced temperature control, company offers pre-tempered chocolate sticks to go with printer. Kickstarter project 2021 (26 backers pledged EUR 38,878 (of EUR 15,000); Company offers bespoke printing services	Fully commercialised
Felix Printer (NL) SINGLE , TWIN and SWITCH food 3d printers	Pastes, Chocolate, Purées, Meats	Single food printer can extrude 1 type of food, twin food printer extrudes 2 foods simultaneously and SWITCH allows to switch between 2 foods.	Fully commercialised

ByFlow (NL) Focus	Various	This food 3D printer mostly targets professionals in the bakery industry; refillable cartridges containing any sort of paste-type food; access to downloadable recipes; Not exclusively food, also thermpolastics (e.g. PLA), ceramic; company holds patent for print head; Company also works with Verstegen Spices & Sauces B.V. – in 2019 the companies announced a partnership where Verstegen would deliver the food inks and ByFlow the printers. “Buyers will initially have the following choices: Beetroot with cardamon, Hollandaise, and curry with ginger”.	Fully commercialised

Shiyintech (China) Foodbot S2 Foodbot D2	Chocolate and other (e.g. toffee, cream, mashed potato)	S2 is a single extrusion model, D2 can print two materials concurrently. Company stresses hygiene: Food filament never touches the printer as it comes in disposable plastic dispenser.	Fully commercialised
Natural Machines (Spain) Foodini	Various	Allows printing with up to 5 cartridges at the same time. Allows creation of complex foods (jelly, pizza, spaghetti, “all the way up to a burger”); Company works with Nestlé and PepsiCo; holds patents on food heating method using lasers.	Fully commercialised (available to rent & purchase from website)
Print4Taste (previously: Print2Taste) (Germany) Mycusini 2.0 Procusini 5.0 Previously: Bocusini	Mycusini: chocolate Procusini: chocolate, marzipan, pasta	Mycusini is a home chocolate printer that works with included special tempered chocolate refills. Procusini is a professional model currently only sold B2B. Company also offers 3D printing services on website; IP on printer and food compositions	Fully commercialised

La Pâtisserie Numérique (France) Cakewalk (attachment) Patiss3	Not specified	Cakewalk in an extruder system that can be fixed to a variety of 3D printers. Patiss3 is a purpose designed food 3D printer based on cakewalk. Company also offers courses in 3D printing for pastry.	Fully commercialised
Wiiboox (China) Sweetin LuckyBot (attachment)	Chocolate, mashed potato, fruit jam, bean paste, other	Wiiboox offers 3D printers for a variety of materials. LuckyBot is an attachment that can be installed on most FDM/FFF printers (incl. Creality, Ender, and others) in order to extrude different food types. Wiiboox clients include P&G and Jaguar. Sweeting is a purpose designed food printer with 100 micron precision.	Fully commercialised
Mmuse (China) Desktop/Touchscreen 3D printer	Chocolate	Uses solid chocolate beans as 3D printing input material.	Available online via edprintersonlinestore.com

Beehex (USA) 3D Dessert decorator Cake Writer Pro™	Cake decoarations	Company offers a range of small to mid-sized 3D cake decorators for businesses; 3D Dessert decorator is specifically for bakeries to streamline production – six colours per design. The Cake Writer Pro™ is thought to be placed inside a shop for customers to print their own cake decorations.	Fully commercialised
Ningbo Createbot Technology Co (China) 3D food printer (not on market any more)	Chocolate, biscuits, bean pastes, other food	3D food printer, no evidence of this any more on current company website.	Not on market any more
CURRANT 3D Printer	Sugar	Designed for professional food manufacturers. The company started off as “Sugarlabs”, was then bought by “3D Systems” and recently sold back again to former “Sugar Labs” founders who have since developed it further.	Fully commercialised

ChocoL3D (Ukraine) ChocoL3D Kit (attachment)	Chocolate	small attachment for chocolate extrusion to fit a variety of 3D printers.	Currently not on market
Structur3D (Canada) Structur3D Discovery Paste Extruder (attachment)	Various pastes	A universal paste extruder for desktop 3D printers. This extension was a Kickstarter project in 2014 and raised CA$ 126,086 from a pledge of CA$ 30,000 goal.	Was commercialised, currently not on market
Foodjet (NL) High speed 3D chocolate printer	Chocolate	Foodjet already offers depositing technology for decorations. The company showcased a standalone 3D chocolate bar printing system capable of producing large numbers of products.	In development
Cocoa Press (USA) 3D chocolate printer	Chocolate	Temperature controlled enclosure, dynamic touchscreen and food safe steel extruder that supports printing with any chocolate. Price on website relatively expensive (USD 9995).	Commercialised

Table 7: Other 3D food printers which have been developed, but where there is currently no evidence of commercial activity.

No recent media or press releases. Some only have demo videos and there is no indication that they have been on the market.

Company name and printer models	Food type	Capability/ USP	Commercial status
Chocoformer (Switzerland)	Chocolate	n/a	No evidence of commercialisation
Shoggi Print (Switzerland)	Chocolate	n/a	Company claimed printer will be available in Feb 22, but no evidence of commercialisation yet
Chocola3d (Ukraine)	Chocolate	Offer services, unclear if their own printer was ever commercialised	No evidence of commercialisation
ChefJet (USA)	Sugar	Was developed by 3D systems using Sugarlab's technology. Many press releases going back to 2013/14, however no evidence of it being on the market.	No evidence of commercialisation

Table 8: List of 3D printer companies which have experimented with food printing, but do not have purposefully designed food printers on the market at the moment.

Company name and printer models	Food type	Capability/ USP	Commercial status

Zmorph (Poland) Zmmorph i500, Zmorph VX, ZMorph Personal Fabricator 2.0 SX	Not specified	Currently on Zmorph Fab and Zmorph i500 website (company also produces Zmorph Shape, a vacuum former). While occasionally listed as a food printer , Zmorph do not certify that the printer's food prints are edible or take any accountability for that.	Fully commercialised, but currently not for food use
Wasp (Italy) Wasp2040	Not specified	Company experimented with food, e.g. preparing gluten free food . Also used for food packaging (cups) at an exhibition, but no commercial food printing model available.	Fully commercialised, but not for food use
ChefJet Cocojet	Sugar	Company had bought "Sugarlab" and then created ChefJet, but no evidence that this was ever fully commercialised. Sugarlab's founders have now bought back technology and created CURRANT 3D Printer. CocoJet is a 3D printer that was showcased in 2015 together with Hershey's, but no evidence of commercialisation.	No evidence of any significant number being sold (if ever).

Table 9: Well-known food companies and other large companies using 3DFP. Some may not have unveiled and/or commercialised a printer, but all companies have expressed that they are working on food printing concepts. Only a couple of large players have an active project (e.g. Barilla).

Company name	Food type	Capability/ USP	Commercial status

Barilla (Blue Rhapsody)	Pasta	3D printing of pasta – service offered to professionals (e.g. restaurants), some shapes available for general consumers. Technology was developed in collaboration with TNO (NL).	Commercialised
Mondelez (Cadbury) & 3P Innovation (UK)	Chocolate	K company 3P innovation worked with Mondelez to develop a 3D food printer “to develop a new way to manufacture Cadbury Dairy Milk. The multi-lane technology can print a range of chocolate shapes and sizes, without using a traditional moulding process”.	No evidence of commercialisation
Nestlé (Switzerland)	Various	In 2014, press release that “Nestlé wants to meet dietary needs with 3D food printing” described research into personalized nutrition (“Iron Man Project”).	No evidence of commercialisation
Katjes (Germany)	Gums	Katjes developed a “Magic Candy Factory” – a gummy 3D printer which was aimed to be released in the US, UK and Germany by 2016. The printer would have taken about 5 minutes to create gummy candy between 15 g and 20g; The company filed a patent on this.	No evidence of commercialisation
Frito Lay (USA)	Potato chips	IP in 3D food printing (WO2022076368A1). Article in press suggests 3D printed potato chips – no further evidence found.	No evidence of commercialisation

Barry Callebaut (Switzerland) (Service available in UK according to website)	Chocolate	Claim to operate the "first chocolate 3D-printing studio in the world" . say they use the "same chocolate couvertures preferred and used by the world's most renowned pastry chefs and chocolatiers." – and deliver to the doorstep. Service available in UK according to website.	Commercialised?

Table 10: Startups - small concept companies.

Company name	Food Category	More info	Commercialisation / Funding
Gastronology (NL)	Food for dysphagia patients	Aim to sell food printers & printed food into hospitals and care homes etc. for dysphagia patients.	Pre-commercial
Remedy Health/ Nourished (UK)	Personal nutrition	3D printing of personalised supplement gums, claim "patented vegan encapsulation formula" and "able to combine 7 active ingredients from 28 choices".	Commercial; In 2020 achieved the largest-ever seed round by a female founder in the UK, £1.95 million. In 2021 raised £8 million in Series A funding after seeing the company's revenues grow by more than 600% over the previous year.
Upprinting Food (NL)	Food waste	3D printing food from retail food waste.	Unknown
Foodink (UK)	Various	This was a one -off event (25-27 July 2016) with a subsequent "world tour" but seemed to have seized to exist.	One- off, no more updates

Company name	Food Category	More info	Commercialisation / Funding
Fab Café (Japan)	Chocolate	In 2013 a press article suggested that for 6,000 Yen (£40), you can have your head scanned and turned into a 3D digital model, which is then printed in plastic in high definition on a ProjetHD printer. A silicon mould is made from this positive form and filled with melted chocolate – and the final product can be gifted in a box of chocolates.	No recent evidence of this service
Chocolate3.de (Germany)	Chocolate	Company developed printer in 2021 (Kickstarter project), but also offers services in printing bespoke chocolate shapes.	Fully commercialised
3D Chef (NL)		This company started with 3D food printing, but now focuses on producing customised moulds for foods. Website states "Before, moulds, thermo-forming, pastry competitions and stencils, 3DChef was pioneering 3D food printing. This is not to say we no longer have an interest in the area, its only that the area did not go the way we would have liked it to. I still see areas of development and some of those we are working on behind the scenes. My focus was always on production environments and not desktop dinky units."	Ceased operations in 3D food printing, now focuses on producing moulds.

Company name	Food Category	More info	Commercialisation / Funding
La Miam (Belgium)	Chocolate	Relatively small company, specialising in customised chocolates. The company also offers laser engraving in macaroons.	Fully commercialised
Open Meals (Japan)	Sushi	Sushi restaurant 3D printing sushi; Wants to engage in developing printer / software, making the actual printed food and selling it to customers in restaurants. Claims production of food ingredient cartridges. These contain sustainable food ingredients, such as seaweed and crickets, which are mixed with water, fibre, and enzymes for printing; On website company claims: "cell cultured tuna" and "powdered sintered uni" or “selective laser sintering of sea urchin powder and rice flour”; "Development of the world's first operating system to design food digitally is underway"	Operating company, unclear about state of commercialisation
Babinese Lollipops (France)	Lollipops	A shop in Paris using Ultimaker for printing Lollipops.	Ceased operations
Smart cups (USA)	Drinks in cups	This is referred to as “3D printed”, however, in an interview the founder declared it was not actually 3D printed. Beverage powder is printed into cups, so users only have to add water for soft drink.	Commercialised, products available from website

Company name	Food Category	More info	Commercialisation / Funding
Sugar Lab (USA)	Sugar	Offering bespoke items created by binder jetting technology. See information on Chefjet and CURRANT 3D printer	Commercialised
Novameat (Spain)	Plant based meat alternative	NOVAMEAT produces plant-based meat substitutes through advanced food printing and tissue engineering technologies. In 2022 Novameat secured $6 million pre-Series A funding.	Commercialised
Revo Foods (formerly Legendary Vish) (Austria)	Plant based seafood alternatives	Company claims plant based seafood produced with 3D food printing. There are questions whether this company uses “real” 3D food printing. Claim products are available in Austrian supermarkets and also in the UK.	Commercialised
Steakholder Foods (formerly MeaTech 3D) (Israel)	Cultured meat	With proprietary 3D bioprinting technology and advanced cellular biology, the company is developing whole-cut, ground and hybrid products. Steakholder Foods has raised a total of $17.9M in funding over 6 rounds.	Pre-commercial stage

Company name	Food Category	More info	Commercialisation / Funding
Redefine Meat (formerly known as Jet Eat) (Israel)	Plant based meat alternative	Ingredients including soy and pea proteins, chickpeas, beetroot, nutritional yeasts and coconut fat. The company has a partnership with meat importer Giraudi Meats to drive European distribution. They operate "large – scale meat printers" at HQ in Tel Aviv and a new factory in NL. Redefine meat is now offered in Loetje restaurant food chain in the Netherlands.	Commercialised
Chef-It (Israel)	Printing burgers	An on -demand printing veggie burger machine.	No evidence of commercialisation
FabRX (UK)	3D printed medicine, inc nutrition.	Company focused on developing 3D printing technology for fabricating pharmaceuticals and medical devices. IP (WO2021160999A1). Company's project pipeline shows nutraceuticals in clinical trials phase.	Pre-commercialisation
Jan Smink (NL)	Restaurant using 3D food printer	Apart from the restaurant, Jan Smink also offers services including food styling, product development and demonstrations and workshops with a 3D food printer.	Commercialised
Dinara Kasko (Ukraine)	Chef	A pastry chef in Ukraine using 3D printing for her creations. Available products on Amazon however are mainly pastry moulds.	Unknown whether there are any 3D printed products sold in a pastry shop or 3D printing only used for developments

Company name	Food Category	More info	Commercialisation / Funding
Print Cheese (NL)	Cheese printing	Dutch dairy farmer who also operates a 3D food printer, but no recent evidence of this being commercialised.	Status unclear
Chocola3d (Ukraine)	Chocolate	Offer chocolate printing services on their website, unclear if their own printer was ever commercialised.	Services seem commercialised
Chocolate Prints (Switzerland)	Chocolate	Tiziana Schraner from Switzerland offers bespoke creations on her 3D chocolate printer and also offers “live” services at events.	Commercialised
La Enoteca (Spain)	Various	Restaurant which uses Natural Machine’s Foodini, 3D printer according to press content in 2016/2017 – no recent information.	n/a